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A STUDY OF FLOODING IN PACKED COLUMNS

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A STUDY OF FLOODING IN PACKED COLUMNS

INTRODUCTION

Packed columns are used in acid manufacture where corrosive fluids are contacted, in humidification where simplicity is of primary importance and in distillation in those instances in which low pressure drop is desired, as for example in vacuum operation. They find particular advantage under those conditions in which the trays in a tray tower would be too close together or the column diameter too small to allow the entrance of workers into the space between trays.

Packed Columns

A packed column has the advantage of simplicity of construction over other types of equipment for contacting gases and liquids. It consists of a column filled with a loose porous bed of packing and a distributor for dispensing incoming liquid over the top of the packing. The liquid flows by gravity down through the packing and is removed at the bottom of the column. Provision is made for admission of gas at the bottom of the column and its removal from the top, allowing countercurrent contact between gas and liquid. Fabrication costs are much less for packed columns than for other types of liquid-gas contacting equipment such as bubble cap towers in which each cap and each tray require many fabrication operations. Packed columns and the packing for them can be made of non-corrosive materials with little regard for fragility or friability since there is no movement of parts during operation. Thus, glass and ceramic ware are quite common construction materials for this type of equipment. For a given gas through-put the pressure drop is considerably less for a packed column than for a tray type column, with consequent lower pumping costs.

Flooding Characteristics

In countercurrent flow of liquid and gas in a packed column there is, for every given liquid flow, a maximum gas flow that will allow countercurrent contact without flooding. Likewise for each gas flow there is a maximum liquid flow above which the liquid becomes the continuous phase and the column operation has reached what is termed the visual flooding point. At these relative flow rates and at greater ones the contact is no longer countercurrent. A given incremental increase in flow requires much greater expenditure of energy than before and liquid is forced out the top of the column into the gas exit. These conditions reduce transfer efficiency and increase cost of pumping, and therefore the flooding condition is avoided in general practice. The final choice of dimensions must be based on an economic balance between the fixed costs of tower construction, which depend on height and diameter, and the operating costs, which are dependent on through-put, as has been pointed out by Badger and McCabe (1).

Flooding limits the extent to which the diameter of a column may be reduced, with any given through-put and packing. Accurate prediction of flooding conditions for a particular system is therefore important for economical design.

Definition of Flooding Velocity

Since the rapid increase in pressure drop with increased flow rate is a characteristic of flooding, both White (2) and Mach (3) defined as the flooding point those conditions under which the slope of a plot of the logarithm of the pressure drop across the column versus the logarithm of the mass flow rate of the gas (at constant liquid flow rate) changed abruptly from approximately 1.8 to a very large value (approaching infinity). It has become customary in the study of flooding to select the liquid flow rate as the independent variable and to maintain it constant while determining the pressure drop across the column for each of several gas flow rates in the range just below and at the flooding point.

Existing correlations, unfortunately, do not give precise flooding rates over a wide range of variation of the many variables which affect flooding. Each of the generally accepted methods of correlating flooding data is satisfactorily accurate only for limited ranges of variables. Rarely has it been possible to extrapolate to conditions outside the range actually investigated, or to apply the correlations to other packing types or other fluid systems. It is the purpose of the work presented in this thesis to correlate flooding data over the range of conditions generally found in packed column practice and to extend these correlations to the new considerations of packed height, adjusted surface tension and wetability of the surfaces of packing and column walls.

Correlation of Flooding Conditions

Work of Sherwood, Shipley and Holloway

Sherwood, Shipley and Holloway (4) devised the first accepted general correlation for flooding conditions. It has been used for a wide variety of column packings, although it is specifically recommended by its originators for dumped Raschig rings. Data were used for 1/2 inch carbon Raschig rings dumped to a height of four feet in a two inch column to obtain this correlation. These investigators discussed White's definition of flooding but used visually observed points. Flooding rates for air, carbon dioxide and hydrogen against water and for air against various aqueous mixtures were measured and used to represent variations in liquid and gas density, and liquid viscosity and surface tension. Viscosity was varied independently over a thirty fold range by changing the concentration of aqueous glycerol. Surface tension was varied independently over a two fold range by addition of different amounts of butyric acid and of methanol to water.

The pore diameter of a packed column characterized by the hydraulic radius, was derived by Fair and Hatch (5), involving porosity and specific surface and was used to characterize packing type and size. The dry packing was dumped into the column and the number of pieces per unit volume required were counted. Without mentioning the source or method of determination, the volume and surface of a "representative" packing piece is reported by Sherwood et al. and these values were used to calculate the porosity and the surface per unit volume of the packed section used.

The data thus obtained correlated quite well on a single curve when plotted as logarithm $\frac{U^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$ versus logarithm $\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{\frac{1}{2}}$, where: S is specific surface, $Ft.^{-1}$

F is porosity

g is gravitational constant, 32.2 $Ft.\ Sec.^{-2}$

U_o is superficial* linear gas velocity, $Ft.\ Sec.^{-1}$

ρ_L is liquid density, $Lb.\ Ft.^{-3}$

ρ_G is gas density, $Lb.\ Ft.^{-3}$

μ is viscosity, centipoise

L is superficial* liquid mass velocity, $Lb.\ Sec.^{-1}\ Ft.^{-1}$

G is superficial* gas mass velocity, $Lb.\ Sec.^{-1}\ Ft.^{-1}$

Variation of these data from the recommended curve was of the order of plus or minus fifteen per cent for the density and viscosity correlations. The maximum deviation from the recommended curve for variations in surface tension was about thirty per cent. The conclusion was drawn that surface tension of the liquid had no appreciable effect on flooding.

Work of Uchida and Fujita

The data of Uchida and Fujita (6) for 0.6, 1.0 and 1.4 inch Raschig rings and for "broken solids" in twelve inch column, that of White (2) for 0.5 and 1.0 inch Raschig rings in three and five inch columns respectively, and that of Baker, Chilton and Vernon (7) for a wide variety of packing types in three, six, twelve and twenty-four inch columns are presented by Sherwood et al. on their type of plot. All data for Raschig rings in all sizes of column are correlated with less than twenty per cent deviation. Other packings, such as Lessing

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*Based on the empty column.

rings (7), deviate as much as one hundred per cent. The one datum of Baker et al. for Berl saddles (one-half inch) is shown to fall thirty five per cent lower than the Raschig ring correlation.

The method of correlation is based on an original suggestion by Sherwood (8). Walker, Lewis, McAdams and Gilliland (9) applied the method to a few data with reasonable success. They visualized flooding as the result of friction between rising gas and descending liquid streams and characterized the flooding condition as that at which the friction per unit height of column equals the liquid hydrostatic head over the same height.

Work of Bain and Hougen

Bain and Hougen (10) packed an eight inch diameter column to a height of four feet with five different packing materials: one-half inch and one inch Raschig rings, one inch and one and one-half inch Berl saddles, and one-half inch wire helices. Their technique was to fill their column with liquid and to drop the packing pieces, one at a time, into the column at such a rate that no piece touched another as it descended into place. After completion of this packing procedure liquid was circulated through the tower "to stabilize the packing" before any data were taken.

The porosity of this bed was obtained by measuring the weight and density of the liquid drained from the packed column while the liquid level fell a measured distance. Surface areas recommended by the packing manufacturer are presented. The investigators do not explain their use of higher values for surface in the cases of the one inch and the one and one-half inch Berl saddles.

The appearance of the column under flooding conditions was observed to be different for each packing type. With Raschig rings a layer of liquid built up on top of the packing. The liquid layer originated at the bottom of the Berl saddle packings and increased in height until it filled the column. "The flooding velocity established from the pressure drop curves occurred when the column was approximately one-third filled with liquid." In the case of the helices, slugs of foam rose through the packing under flooding conditions but the column was never filled with liquid. The White definition of flooding was found to described reproducible conditions in all cases and was therefore used.

Flooding rates were measured by Bain and Hougen for three oils, having viscosities of two, five and one-half and twelve centipoise, against air, hydrogen and carbon dioxide. Their data were presented by means of the correlation suggested by Sherwood and were compared with his recommended curve.

The data of Bain and Hougen for Berl saddles were consistently thirty five per cent high on the Sherwood plot. Their data for Raschig rings and helices, on the other hand, fell thirty five per cent low except at relatively low liquid rates where his curve crossed that of Sherwood. They also presented their data on a log-linear plot, that is, as logarithm $\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$ versus $\left[\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{\frac{1}{2}}\right]^{\frac{1}{4}}$ and obtained two straight lines, one for Raschig rings and helices and another sixty five per cent above it for Berl saddles, both of which fitted the data with a maximum deviation of twenty per cent.

Work of Elgin and Weiss

Elgin and Weiss (11) packed a three inch diameter column successively with one-half inch Berl saddles, five-eighths inch Raschig rings, one-half inch clay spheres and one-fourth inch Berl saddles to a height of 4.67 feet. The tower was filled in each case by dumping. In the case of the one-half inch saddles and the five-eighths inch rings the packing was "leveled off and otherwise adjusted to fill in large free voids appearing adjacent to the walls at intervals during the process of packing". Free void space was determined by draining liquid from a measured height of column. A lack of standard uniformity in the packing materials and the large probability of the existence of "wall effect", especially in the case of the large packing sizes, are admitted. The packing support was wire screen of mesh just small enough to retain the packing pieces.

The only fluids studied by Elgin and Weiss were water and air. A period of 30 to 60 minutes, during which flow rates were maintained constant, was specified as necessary for attainment of steady state, after which time the data was recorded. The flooded condition was reported as having been attained when the packed section slowly filled with water. This phenomenon began in the lower section of the tower in the majority of runs and with the flow rates constant the liquid rose to a fixed level above the packing. It was found possible by "extreme regulation" and patience to so adjust the gas flow that the level of liquid remained at the top of the packing and this was taken to be the true flooding point. This condition was found in all cases to be quite close to the flood point as defined by White. Elgin describes the curve of the logarithm of pressure drop versus the logarithm of gas velocity as a continuous curve having no "breaks".

Using the Sherwood type plot and compared with his recommended curve, the data of Elgin and Weiss would lie on a curve of the same general shape but fifty per cent below Sherwood's curve.

Work of Schoenborn and Dougherty

Schoenborn and Dougherty (12) packed their eight and five-eighths inch diameter column to a height of two feet with five different commercial packings. One inch carbon splined rings, one inch ceramic rings, one-half inch porcelain rings, one-half inch Berl saddles and one-fourth inch carbon rings were used. These were charged into the column (after it had been filled with liquid) by dropping them in "by hand". It was expected that this would "obtain uniform distribution of the packing" and would "simulate industrial practice".

Flooding velocities were measured for air with water and two oils having viscosities of fourteen and thirty-five centipoise. The flooded condition was characterized as that under which a "head grew on the packing" and the liquid stood approximately one-half inch above the top of the packing. With Berl saddles, flooding was first noticed as a violent disturbance at the base of the packing which within ten to fifteen minutes worked itself up through the packing until a head of liquid was firmly established at the top. The oils did not appear to build up as a layer of liquid on top of the rings at flooding.

Instead, violent spraying of fine oil droplets was noticed and the flooding point was taken as that gas velocity causing the first appreciable amount of liquid carry-over. The visual flood point was not found to coincide with that determined by a plot of pressure drop against gas rate and no relation was found between the two. The visual point was sometimes at greater and other times at lower flow rates.

Schoenborn and Dougherty presented their data plotted as logarithm $\frac{G}{\phi}\nu^{n}$ versus logarithm $\frac{L\phi}{G}$, where

G is superficial gas mass velocity, Lb. Sec.$^{-1}$ Ft.$^{-2}$

L is superficial liquid mass velocity, Lb. Sec.$^{-1}$ Ft.$^{-2}$

ϕ is $\left(\frac{\text{density of gas}}{\text{density of air}}\right)^{\frac{1}{2}}$ which equals unity in this case

ν is kinematic viscosity of liquid in centistokes

n is an exponent which varied from 0.12 to 0.33 depending on the type of packing.

For any one packing the suggested method of plotting fit the data within fifteen per cent. Since none of the characteristics of the packings were included in the correlation, it could not be expected that any relationship between the curves for different packings would be found.

Work of Sarchet

Sarchet (13) used the same eight and five-eighths inch column and other equipment which later was used by Schoenborn. He described the packing support as a spiral of one inch strip of steel 1/32 inch thick with about three-eighths of an inch between successive turns.

This support was mounted on three 2 inch legs and a section of minimum cross section at the bottom of the column was thus avoided.

Three types of packing were used: one inch and one-half inch clay Raschig rings and a special one inch carbon ring with straight lateral ribs inside and out. The column was packed to a height of two feet by "dropping the packing" into the column which was filled with water.

Flooding was observed using air against water and the flooding condition was defined as that under which water built up on top of the packing to a depth of one-half inch. It was found possible to so adjust the gas rate that the water level could be maintained at any level above the packing up to four inches, which condition corresponded to the limit of capacity of the air blower used. In this condition, movement of the rings at the top of the column was noticeable and their rattling could be heard. Sarchet reports that for different types and sizes of packing "there is no apparent correlation between the visual flooding point, as indicated by the velocity at which water began to build up on top of the packing, and the graphically determined flooding point of White".

Sarchet presented his measurements in tabular form. Without showing calculations or actual points on his plot of G/ϕ versus $L\phi/G$, he recommends curves for his data on different sizes of rings and compares them with curves on the same co-ordinates representing the data of Mach, White, Sherwood <u>et al.</u>, Elgin and Weiss and Uchida and Fujita. All the data so presented were for rings except some for "broken solids" reported by Uchida and Fujita. The curves have the same general shape, but vary as much as one hundred per cent in gas velocities.

Work of Baker, Chilton, and Vernon

Baker, Chilton, and Vernon (7) studied the distribution of water in packed columns as a function of the distance down the column from the top of the packing. One inch and one and one-half inch Berl saddles as well as a rather wide variety of other packings were used in three inch, six inch, twelve inch, and twenty-four inch columns. They found uniformity of distribution over the top of the packing to be essential, but concluded that redistributors in the column were unnecessary. When the water was admitted at a central point onto one-half inch Berl saddles in a six inch diameter column with no gas flow, the liquid distribution was uniformly concentrated in the areas near the walls after descent of four feet or more. The same size saddles in a twelve inch column showed the water to be still concentrated near the center of the column at four feet (the lowest point measured for this case). For one inch saddles in a twelve inch column with central feed, the distribution at a level four feet down from the top was changing rapidly toward a predominance at the walls. For both sizes of saddles in a twelve inch column with a four point distributor, the distribution was more nearly the same throughout the four foot section measured but there was a trend toward predominance at the center near the top which was reversed in both cases before the water had descended one foot.

Very uniform flows were obtained after a three foot descent from central admission in a three inch column packed with one-half inch spheres and this condition persisted throughout the remaining fifteen feet measured. For the same conditions in a six inch diameter column, four feet were required for leveling off of the trends, at which level the flow was concentrated near the walls. With a nineteen point distributor in a twelve inch column with one-half inch spheres the trend was still toward flow concentration near the walls after a four foot descent.

Based on such data for sizes from one-fourth to two inches of many types of packing materials, Baker and his co-workers concluded that wall effects on flow distributions are negligible at ratios greater than eight to one of tower diameter to nominal packing diameter. With such choice of sizes, uniform distribution of liquid flow is "eventually" obtained as it flows down the column.

It was concluded that water rates other than the five hundred Lb. Hr.$^{-1}$ Ft.$^{-2}$ used and countercurrent flow rates of air (at other than flooding velocity) would show the same results. These conclusions were based on investigations of these quantities as variables.

<u>Work of White</u>

White (2) presented the data obtained from several undergraduate research projects at the University of North Carolina. Included were flooding velocities for air against water through 3/8, 1/2, 5/8, 3/4, 1 and 1-1/4 inch Raschig rings in three and six inch columns packed five feet high. Correlation of these data has been presented by

Sarchet, by Elgin and Weiss, and by Sherwood (see above).

Simultaneously, but independently, White (2) and Mach (3) defined flooding as that point on a plot of the logarithm of pressure drop versus the logarithm of the gas velocity at which the slope changes abruptly from about two (fairly constant) to a much higher value.

Work of Other Investigators

Zenz (14) agrees with Elgin that the logarithm pressure drop versus the logarithm gas velocity curve is a smooth one and has no breaks. He characterizes flooding velocity as that at which this curve attains a slope of infinity.

Lobo, Friend, Hashmall and Zenz (15) found Sherwood's correlation to be improved (from a maximum deviation of two hundred and fifty per cent to one of one hundred and twenty per cent) by use of empirically averaged values of the term S/F^3. Based on data available in the literature, these investigators undertook the evaluation of more precise values of the specific surface of packings as packed, S, and the void fraction, F. They found it possible to reproduce within five per cent the value of the ratio with subsequent packed sections using their "dry packed" method. This consisted of dumping the dry packing material into a calibrated experimental tower, adding measured volumes of water and observing the height to which the water rose. This procedure was repeated several times until the packing was just covered and sufficient volume of packing was used so that end effects could be neglected.

Values of S/F^3 comparable to those of the dry packed towers were obtained by "wet packed, shaken" method in which the packing was dropped incrementally into the column containing a known volume of water, while the column was shaken carefully until the packing assumed its most dense arrangement. The total volume of packing and water was measured at several intervals and free voids were calculated.

Materially lower values of the ratio were obtained when the tower was packed by the "wet packed, unshaken" method, described as duplicating common industrial procedure. The method was the same as the "wet packed, shaken" except that the column was not shaken.

The number of pieces required for each pack was determined by total weight divided by the average weight of one piece. Check by actual count proved this method accurate. The surface was then calculated from the average surface area of one piece. In the case of saddles the manufacturer's value for surface of one piece was used.

The evaluations were made on ten different sizes of Raschig rings and six sizes of carbon rings between one-fourth and two inch, and on one-half inch and one inch Berl saddles in six, nine and twelve inch columns. Sherwood's correlation using these experimental values showed slightly larger maximum deviations than with the empirical averages mentioned above, but the predominance of points for the data of Bain and Hougen, Elgin and Weiss, White, Sarchet, Schoenborn and Dougherty, Sherwood _et al._, and Uchida and Fujita is much nearer Lobo's curve, which falls below that of Sherwood by about thirty per cent, according to Zenz (14).

Lerner and Grove (16) suggest as the mechanism of flooding the establishment of waves in the liquid streams. That wave formation begins at some critical relative gas velocity characteristic of the nature of the channel has been shown by Boelter (17) and others. Lerner and Grove successfully correlated the data of Tillson (18), White, Schoenborn and Dougherty, Mach, and Sarchet on a plot of the logarithm of G versus the logarithm of L where G and L are flooding mass velocities of gas and liquid respectively, for both ring and saddle type of packing. Plots of the logarithm of pressure drop across the column versus the logarithm of gas rate show that such curves can be extended beyond the flood point, above which the slope of the curve is again of the order of two. This is the condition in which the liquid stands above the packing and gas bubbles through it.

PURPOSE OF THIS INVESTIGATION

Efforts to bridge the gaps between the results of the work of the various investigators above reported have not been completely successful. A suggested method of correlation, applicable to one set of data, usually fails to correlate successfully the data of others for presumably the same or comparable conditions. Undoubtedly, some investigators must have been in error in choosing the conditions which would be representative of general conditions. Data for a wide range of values of the various variables, all from one centralized program of research, are needed for a proper evaluation of generalized methods of correlation.

This research program began with the realization that Berl saddles require greater care during packing and operation of the column than do some other types of packing. Unless due care is taken columns packed with saddles will not display generalized characteristics of flooding and of absorption efficiency. This disadvantage as far as industrial application is concerned is offset by the greater efficiency and lower pressure drop encountered with saddles as compared to other commercial packing, such as Raschig rings.

Many investigators who have studied the phenomena of flooding in packed columns have been quick to admit the possibility that the conditions met in their work were not generally representative. Others have chosen conditions which are unsatisfactory for representative generalizations. The existing correlations have been weighed heavily with data for packings other than Berl saddles, notably those for

Raschig rings.

The purpose of this investigation was to study the effect of the physical properties of the liquid and gas, column diameter, packed height, and size and type of packing on the flooding velocities. Included in the physical properties of the liquid were adjusted surface tension and "wetability" of the surface of the packing. Method of packing became a facet of the problem when it became evident that a special technique was required for Berl saddles.

This study, therefore, is not only concerned with a re-examination of the work done by earlier investigators which as we have shown are quite inconsistent, but considers also the important factors hitherto neglected, namely, effect of packed height, method of packing, effect of surface energy, and effect of column diameter.

EQUIPMENT AND MATERIALS

Columns

In order to allow visual observations of the flooding phenomena, the column was built of lengths of pyrex glass tubing. Two, four and eight inch diameter columns were used. The tubes were obtained from Corning Glass Works in lengths of four feet. For those packed sections of greater height than four feet, the required number of lengths of tube were sealed together by use of tight fitting synthetic rubber sleeves at the joints.

These glass columns were supported by an angle iron superstructure and were mounted upon a base which would accomodate any of the various diameters of tube. At the foot of the column the tube was sealed with mastic into a metal flange of appropriate size. This flange was clamped down with hold-down bolts to a wide faced flange on the liquid outlet pipe. The gas inlet was mounted inside of and concentric with the liquid outlet. The liquid exit was through a vertical U-tube which served as a barometric leg to seal the bottom of the column. Effluent through this seal overflowed into a ten gallon reservoir from which the circulating pumps took suction. The packing support in all cases was a piece of heavy gage wire screen of one-half inch mesh. Figure 1 is a schematic drawing of the equipment.

Flow System

The two liquid circulating pumps, mounted in parallel, were of the centrifugal type, one Pacific Pump Company Model 105 with

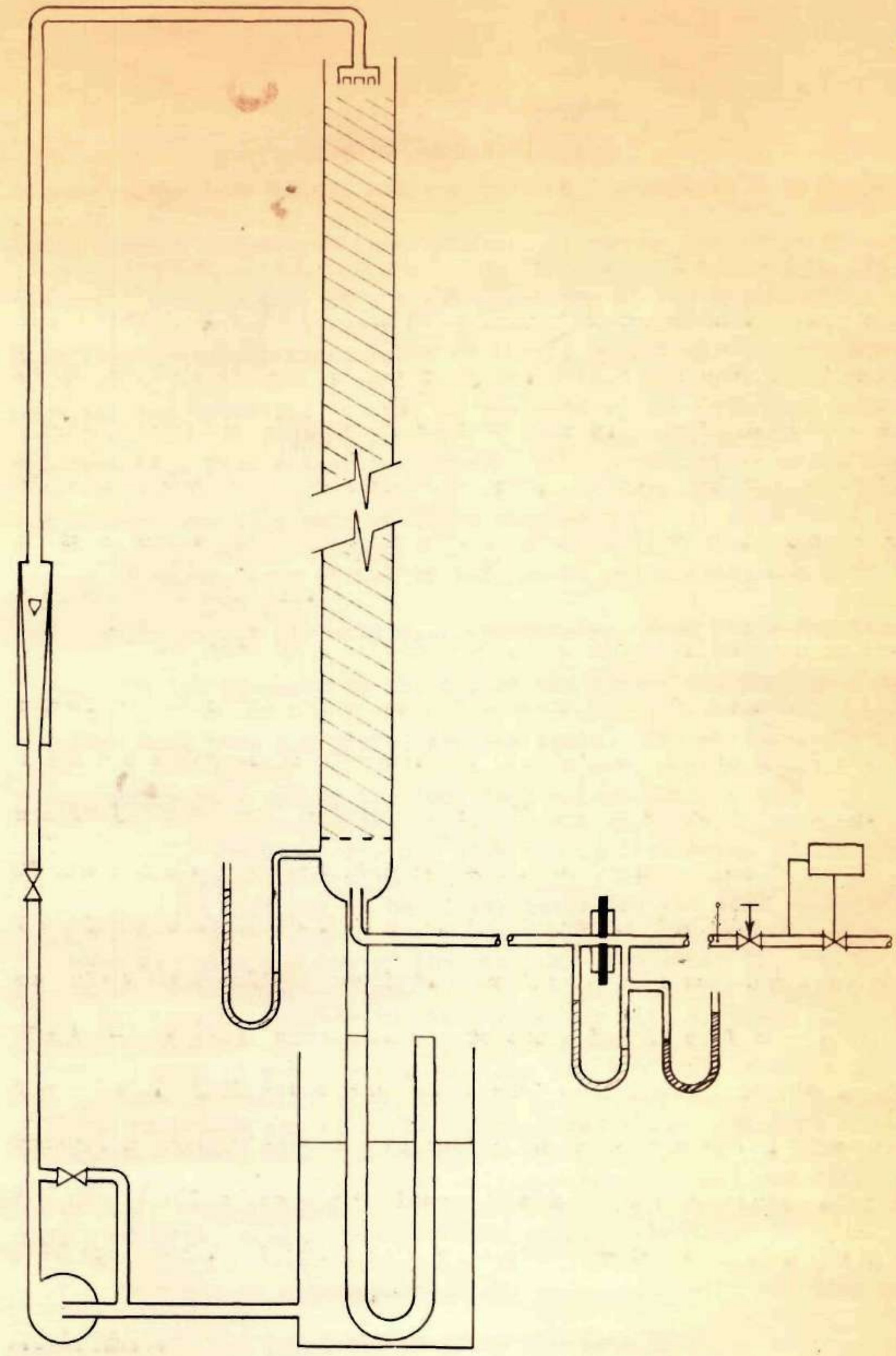

Figure 1.

SCHEMATIC DIAGRAM OF EQUIPMENT

three-fourths inch intake and one Eastern Centrifugal Pump Company Model El with one-fourth inch intake. It was an advantage to have the small pump so that it was not necessary at low liquid rates to have inordinately large amounts of liquid by-passed with consequent churning and excessive foaming in the case of the detergent solutions. The discharge from either pump could, with proper valve arrangement, be led through one of a bank of three Fischer & Porter rotameters having ranges of water flows of 0.1 to 1.2 pounds per minute, and 2 to 18 and 5 to 50 pounds per minute, respectively. From the rotameters the liquid was led overhead to the top of the column and through a distributor head into the packed section again. For the detergent solutions, which were run in the four inch column only, a distributor was made of a two inch pipe cap with four $\frac{1}{2}$ inch holes evenly spaced. This minimized frothing at the distributor and yet gave satisfactory distribution over the top of the packing. For other liquids in the four inch column, another two inch pipe cap with eighteen holes one-eighth inch in diameter was used. For the two inch column a three-fourths inch pipe cap with five holes three-sixteenths inch in diameter was used and for the eight inch column a special head was built of one-half inch pipe, having twenty points of distribution.

In order to obtain maximum air velocities with existing equipment, the air was furnished at 90 to 120 psig by three compressors in parallel. A reducing valve was used to reduce pressure fluctuations. The air at 75 psig was led through a small cyclone with drain to the atmosphere and then through a fibre-glass filter. This assured that the air entering the orifices was dust- and condensate-free. The clean air was throttled through a three-fourths inch needle valve and led into any one of three sharp edged orifices mounted according to A.S.M.E. specifications (19). The orifice and pipe diameters were as follows: a 0.20 inch orifice mounted in a $\frac{1}{2}$ inch pipe, a 0.50 inch orifice mounted in a 3/4 inch pipe and a 1.1375 inch orifice in a 2 inch pipe. The pressure drop across each was measured by water in a 36 inch glass tube manometer so arranged that the connections could be shifted from one orifice to another. The pressure upstream of the orifice in use was measured by a mercury filled manometer. Pressure drop across the packed section during flow was measured by water in a four foot manometer.

Packing Materials

The Berl saddles were obtained from the Maurice A. Knight Company of Akron, Ohio. The manufacturer reports their physical properties to be those presented in Table 1. One inch, three-fourth inch, one-half inch and one-fourth inch saddles were used. The five-eighths inch spheres were glass marbles obtained from Sears Roebuck and Company in Atlanta, Georgia. The author is indebted to Dr. J. M. Lucas of United States Stoneware Company for the loan of the one-half inch Intalox saddles, whose physical properties are presented in Table 1.

Method of Altering Surface Properties of Liquid and Packing

The surface of the packing was made hydrophobic by treating with Dow Corning Resin 803. New Porcelain one-half inch Berl saddles were

Table 1. Physical Dimensions of One Saddle

Berl Saddle	1/4 inch	1/2 inch	3/4 inch	1 inch
Surface, Ft.^{2}				
Ga. Tech.	0.00244	0.00763	0.0187	0.03593
Knight*	0.002425	0.0088	0.0231	0.0344
Volume, Ft.^{3}				
Ga. Tech.	0.00000404	0.00002402	0.0000681	0.0001572
Knight*	0.00000354	0.00002215	0.0000680	0.000139

Intalox Saddle‡	1/2 inch
Surface, Ft.^{2}	0.00933
Volume, Ft.^{3}	0.00001223

*Maurice A. Knight Company, Akron, Ohio.

‡United States Stoneware Company, Akron, Ohio.

heated to 1400 °F. for three hours or more and then allowed to cool. The resin was dissolved in distilled benzene (B.P. 176 $\pm$ 0.5 °F.) and the packing submerged in a three volume per cent solution. The packing was air dried and then baked at 400 °F. for one hour, after which it was allowed to cool and was ready for use.

The column with treated walls was made up of two 4 inch diameter tubes whose clean walls were swabbed with benzene and then with the resin solution and air dried. The tubes were then warmed to about 120 °F. for one-half hour to assure complete evaporation of the benzene.

Materials

The physical properties of the various liquids as used are presented in Table 2.

The surface active materials were aqueous solutions of Sterox S. K. obtained from Monsanto Chemical Company. Enough of this condensation product of ethylene oxide and dodecyl mercaptan was added to water in each case to give the desired adjusted surface tension. Figure 2 is a plot of amounts of Sterox required for various surface tension values between that of pure water and the minimum of thirty-two dynes per cm. for aqueous Sterox. Aerosol OT and sodium oleate were also used, independently, to lower the surface tension of the liquid.

The carbon dioxide was analyzed by caustic absorption and found to be more than ninety-eight per cent pure. The flow was measured with the same orifices used for air. The vapor pressure from the cylinder was reduced to sixty psig by a reducing valve and the flow was through the same cyclone, filter and needle valve as in the case of air.

Table 2. Physical Constants of Liquids

	Density, Lbs./Cu. Ft.	Viscosity, Centipoise.	Surface Tension, Dynes/Cm.
Capella Oil*	55.0	28	31.7
Carbon Tetrachloride[xx]	99.5	0.97	26.7
Ethanol[xx]	49.2	1.5	22.3
Kerosene[x]	50.2	1.6	27.8
Methyl Ethyl Ketone[xx]	50.1	0.42	24.6
Toluene[xx]	55.1	0.58	28.4
Water[xx]	62.2	0.75	72.8

*Properties at operating temperature of 100 °F.

[x]Properties at operating temperature of 75 °F.

[xx]Properties at average operating temperature of 83 °F.

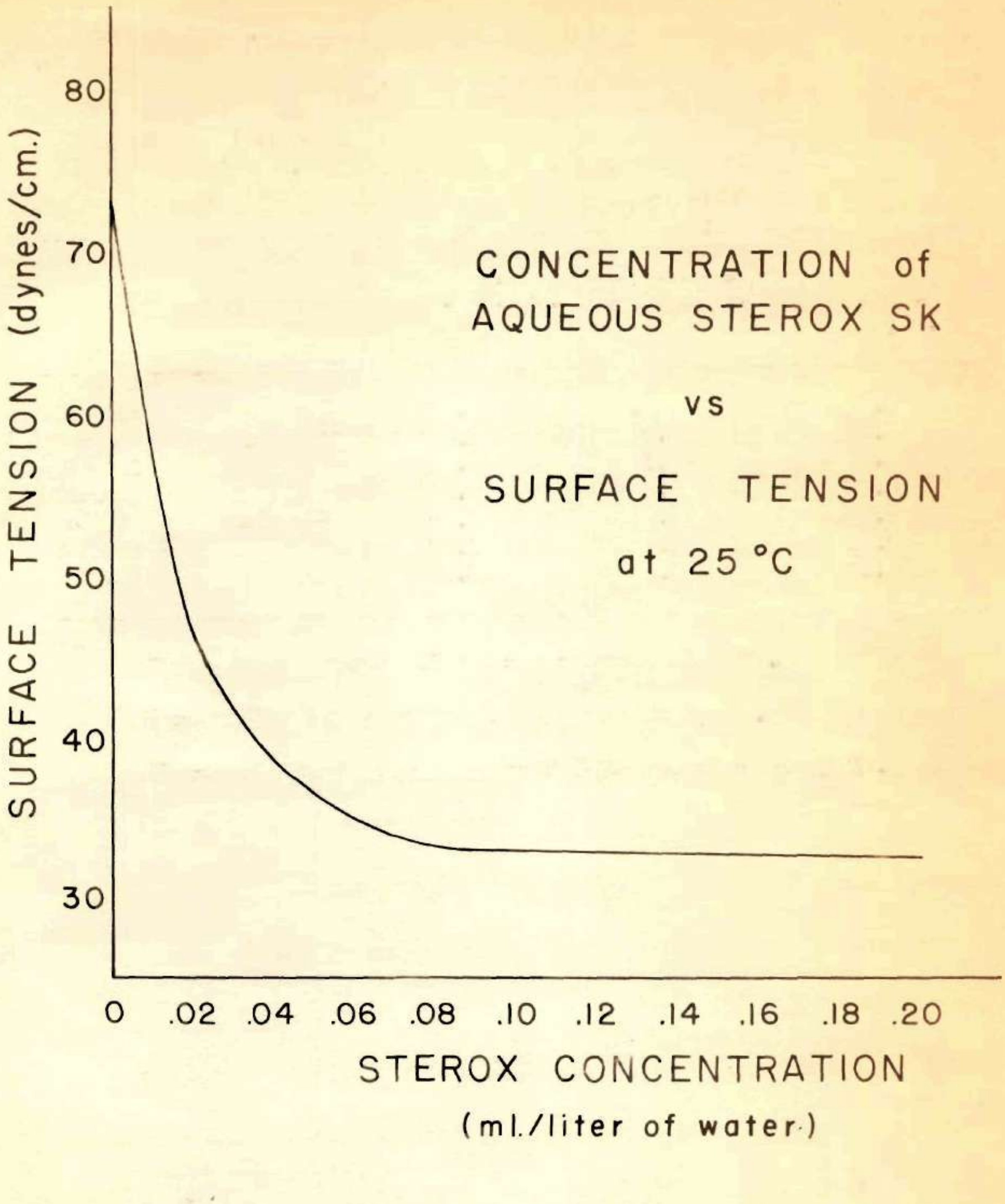
CONCENTRATION of AQUEOUS STEROX SK
vs
SURFACE TENSION
at 25 °C
SURFACE TENSION (dynes/cm.)
80
70
60
50
40
30
0 .02 .04 .06 .08 .10 .12 .14 .16 .18 .20
STEROX CONCENTRATION
(ml./liter of water)

Figure 2.

PROCEDURE

Preparation of Packing

The column was filled with water and pieces of the chosen packing were dropped in, one at a time. In the case of the one-fourth inch saddles a layer of one-half inch saddles was first laid down on the support. In no case did flooding originate at the packing support.

When the column was packed to a calculated height above the desired height of packed section, flooding was simulated by filling the lower portion of the column with water and forcing enough air through to cause all but the top layer of packing to be full of bubbling liquid. It was found that if the top layer were submerged during this operation "nesting" of the saddles took place and the random orientation of the packing pieces was spoiled. Thereafter flooding was more likely to occur at this level than elsewhere in the packed section. This preliminary flooding reduced the porosity approximately five per cent and the level of the packing dropped. Excessive shaking or actually lifting the packing during this preliminary flooding resulted in a pack with non-random orientation of pieces and flooding at lower flow rates. Flowing liquid over the packing to stabilize it as recommended by Bain was found to be ineffective in that the first flooding always caused some settling of the packing. The packing operation was considered to be successful only when the holdup, as evidenced by a fluttering of liquid waves in the gas stream near flooding velocities, was generally distributed throughout the volume of the packed section.

Determination of Packing Characteristics

The difference in dry voids and "drained free volume" was found to be of the order of one per cent when determined with water. Therefore, all porosities were determined from the dry void volume.

The porosity of the bed of packing was determined by completely drying the packing and column by flowing dry air through it. Water was forced into the column from the bottom until its level was about one packing piece diameter above the bottom of the packing. Water was then added at the top of the column until its level was within the same distance of the top stratum of packing. The measured volume of water added to the known height indicated the relative porosity, since the volume of the empty column was known.

The volume of one hundred packing pieces of each size was determined by volumetric displacement of water. The number of pieces per unit volume of any packed section was calculated from this volume and the porosity. The average surface per piece was determined at the Georgia Institute of Technology by scribing a network of lines on the surface of a piece and calculating the sum of the resulting areas. The packing piece was held in a small vise while a marking scribe was mounted on a micrometer adjustment in such a way that extremely fine lines could be scribed upon the surface to be measured. Similarity between different portions of the surface of a Berl saddle allowed the measurement of one portion as one-eighth of the total. The values obtained agreed within fifteen per cent with the manufacturer's reported values except in the case of three-fourth inch saddles. Checks on the method by different measurements of the same piece and on the variation from piece to piece by measuring different pieces increased the confidence in this method and the value so obtained for three-fourth inch saddles was used rather than the manufacturer's. (See Table 2).

Determination of Flooding Velocity

The operating procedure was to establish a constant rate of downward flow of liquid in the column by use of the pump and rotameter appropriate to the magnitude of the flow desired and to maintain a constant rate of upward flow of gas until steady state was assured. No arbitrary time was chosen for this attainment of steady conditions, but the constancy of the pressure drop across the column, at whatever time such constancy might occur, was taken as indicative of steady state. Under this condition the pressure drop across the gas measuring orifice, the upstream pressure and temperature, the liquid rate and the pressure drop across the packed section were recorded.

The first chosen gas rate was one well below the flooding gas rate for the liquid rate being maintained, and was ascertained by experiment if necessary. The liquid flow was held at this constant rate throughout a series of small increments in gas rate and attainment of steady state at each gas rate, yielding data for a plot of the logarithm of the pressure drop across the packed section versus the logarithm of the gas mass flow rate. In each case these data were taken over that range of flow which yielded a pressure drop versus gas rate curve having a sharp break upward at what was termed the "flood point" by White (2). Only in a few cases was this flood point found to differ noticeably from the visual flood point. This procedure was repeated for a number of liquid flow rates, and flooding conditions over a wide range of liquid and gas flow rates were thus obtained.

Experiments With Air and Water

Three column sizes, two, four and eight inch diameter were used. In the two inch column, flooding was studied with one-fourth inch Berl saddles packed to one foot, four feet and seven feet heights, and one-half inch saddles at four and seven feet heights. In the four inch column one-fourth inch Berl saddles, three-fourth inch saddles and one inch saddles were packed to seven feet heights. One-half inch saddles were packed to one foot, three and one-half feet, five feet, seven feet, eleven feet and sixteen feet heights. Five-eighths inch spheres were packed to two and seven feet heights in this size column. In the eight inch column one-half inch Berl saddles were packed to one foot, three and one-half feet and seven feet heights, three-fourth inch saddles to three and one-half feet height and one inch saddles to one foot and three and one-half feet heights. Five-eighth inch spheres were packed into the eight inch column to one foot and three and one-half feet heights. In each of these cases the flooding velocities of air against water were measured over a general range of superficial liquid rates of 0.06 to 4 Lb. Sec.$^{-1}$ Ft.$^{-2}$.

Experiments With Air and Organic Liquids

Another seven foot packed section of one-half inch Berl saddles in a four inch diameter column was checked with air against water over the same range of water rates. Close agreement of flooding rates with those in the seven foot section of one-half inch saddles in the four inch column mentioned above was obtained on a Sherwood type plot. Flooding rates of air against ethanol, toluene, methyl ethyl ketone, carbon tetrachloride, kerosene and Capella Oil (Texas Company) were measured. Among these liquids the viscosity has been varied over a sixty-five fold range from 0.42 to 28 centipoise. The density of the liquids varied two fold from 49.2 to 99.5 Lb. Ft.$^{-3}$ while that of the gas varied from 0.071 to 0.114. Surface tension of the pure liquids varied three fold, from 22 to 72 dynes cm.$^{-1}$. The properties of the liquids under conditions of use are given in Table 3. The viscosity - temperature relationships of the kerosene and Capella Oil were such as to require thermostatic control of the temperature in the liquid reservoir. For the other liquids the average uncontrolled reservoir temperature was used.

Experiments With Carbon Dioxide and Capella Oil

The gas rates required to flood the column at higher rates of flow of Capella Oil were low enough to make possible the use of carbon dioxide from a cylinder to flood the column. Cylinder pressure was reduced to sixty psig with a reducing valve and the carbon dioxide was led into the system through the cyclone.

Experiments With Air and Aqueous Solutions

Still another seven foot section of one-half inch saddles in the four inch column was checked as described above. Flooding rates were measured in this column for air against aqueous Sterox solutions having adjusted surface tensions of sixty-two, fifty-two, forty-two, and thirty-two dynes $cm.^{-1}$. These surface tension measurements were made on a du Nouy interfacial tensiometer.

Experiments With Hydrophobic Surfaces

The four inch column was packed again to a height of seven feet with one-half inch Berl saddles treated to be hydrophobic with Dow Corning Resin 803. Later the same packing was changed to a four inch column whose walls were treated with the resin. This column was also packed seven feet high with untreated one-half inch saddles. In each of these three cases, the flooding rates of air against water were measured over the whole range of liquid flows.

Surface tension measurements on the water for these and subsequent flooding measurements showed no abnormal values. This was taken as proof that no treating material was dissolved or remained in the system after finishing the measurements on treated material.

DISCUSSION

The Effect of Packed Height

In Figure 3 is presented data on flooding with water against air of a four inch column packed with one-half inch saddles to varying heights. It is to be noted that this column contains packing of a size recommended by Baker as permissible for it. It is also evident that between five and seven feet height of packed section is required to eliminate the effect of packed height. The curve for the seven foot section was selected as a "reference" curve for reasons to be explained later. The effect varies as an inverse function of packing height up to about sixty per cent at relatively low liquid rates in a packed section only one foot high. At liquid rates greater than two and one-half pounds per second per square foot the effect is negligible for all cases.

For the case of the same packing size versus tower diameter ratio for a two inch tower (8 to 1), the minimum height for no effect of packed height is shown by Figure 3 to be no more than four feet. By comparison, four feet was found to be insufficient if the packing-tower diameter ratio was reduced, in this case to four to one. For greater values of this ratio represented (on Figure 3) by one-half inch saddles in an eight inch column, the minimum height for no effect of height is no more than three and one-half feet.

One foot packed height was considered to be about the minimum for representative operation; less height would contain too few pieces to allow a statistical distribution of packing piece orientation. For the case of an eight to one ratio of packing to tower diameter, that is, for one-fourth inch saddles in the two inch column, one-half inch saddles in the four inch column and one inch saddles in the eight inch column, the increase in flooding velocities, as represented on a Sherwood type plot, of the one foot over the four foot heights is the same (forty per cent).

These findings are in accord with Baker's results that four or more feet of descent is required, even with a good distributor head, to attain a steady state of distribution of liquids flows in the packed section. The fact that in every case of measurement of the effect of height, that effect was a maximum at low liquid rates and was negligible at high liquid rates contradicts the validity of the assumption by Baker, Chilton and Vernon (7) that their measurements of distribution at one liquid rate were representative of all liquid rates. Their conclusions that some distance of descent is required for equilibrium of distribution (even with a good distributor) at gas rates up to and including the flooding gas rate is substantiated.

For assurance of adequate distribution from the distributor heads used on this project, check runs under the same conditions except manner of distribution were made. No noticeable effect was discovered for variation of number or size of distribution points or of height (up to three inches) of head above the packing. In no case was formation of spray nor direct impingement of a jetted stream upon the packing allowed. Rather, the streams were directed other than vertical and allowed to follow a trajectory path before falling gently onto the packing.

There is competition between the liquid and the gas for disputed passageways for flow. If the packing is wetted, the liquid at steady state of distribution flows over it as a film and the center portion of each pore is left open for the flow of gas. There is, under these conditions, maximum opportunity for attainment at a given gas flow of the critical flow described by Lerner and Grove (16). Above the level at which this equilibrium in liquid distribution is achieved, some passages are completely filled by liquid and others relatively free of liquid, so that there are larger but fewer passages available for gas flow and the critical flow required for flooding is therefore higher.

In a column properly packed, that is, with the highest possible degree of random packing piece orientation throughout, from bottom to top stratum, that portion of the packed section from the bottom up to the level at which equilibrium of liquid distribution is attained has the highest possibility of containing the point "weakest" in resistance to flooding. This explains the observation of Elgin that flooding began in the "lower section of the tower" but is not to be confused with the explanation of flooding originating at the packing support as observed by Bain and Hougen (10) and by Schoenborn and Dougherty (12). The assurance of Baker, Chilton and Vernon of "eventual" accomplishment of equilibrium distribution allowed a formulation of choice packing size for a given tower but the effect of height on flooding has been neglected.

In keeping with the observation of Baker, Chilton and Vernon of distribution over one-half inch spheres, it was found that there was an effect on flooding of heights of packed section of the five-eighth inch glass spheres used in the four and eight inch diameter columns. Figure 10 is a plot of these data.

The Effect of Column Diameter

The wall of a column presents to a packing piece, in contact with it, a much different surface from that presented by a vertical layer of packing pieces. In the case of the smooth wall there can be no interlacing of protrusions and the resulting passageways between the wall and adjacent pieces is more open than those between pieces within the packed section. Such a condition is conducive to channeling at the wall with consequently greater difficulty of flooding as was shown by the results of flooding in the hydrophobic packing. The less the curvature of the wall, the less conformity with an individual packing piece exists; and the wall effect is therefore greater for those walls having less curvature. The larger the column the greater the difference in pore size between wall and center portion pores.

For a given size of packing, the flooding rates should therefore be higher in large than in small columns. The data for one-half inch saddles in the three sizes of columns, all at heights at which the effect of height is negligible, show this trend (see Figure 4). Data for one-half inch saddles in the two inch column fall twenty-five per cent lower than those shown for the one-fourth inch saddles in that column. Elgin, using a small column with packing larger than the eight to one ratio recommended by Baker, found his column to be easier to flood by about fifty per cent. The fact that Sherwood obtained representative results with small ratios in a small column is attributed to the fact that this effect is much less for Raschig rings, as is shown by McManus (19) who used the same column and measuring equipment as the author to measure flooding over porcelain rings. The effect is less for rings due to their greater conformity to the contour of the tower wall, as noted above in the discussion on preferential orientation.

The Effect of Packing Size

Observing the requirement that the ratio of packing pieces to tower diameter be equal to or greater than eight to one, Sherwood's correlation allows a satisfactory fit of all data obtained here on tower diameter and packing size. Thus Figure 3 shows that for one-fourth inch saddles in a two inch column, one-half inch saddles in a four inch column, and one-half inch saddles in an eight inch column, the maximum deviation is less than that found by Sherwood *et al.* among the data of other investigators. In each of these cases the height is sufficient to make its effect negligible, and the ratio of tower diameter to packing size is eight to one or greater.

From Figure 4 it can be seen that the method correlates well the effect of packing size. The data for all four sizes of saddles in the four inch column at seven foot height lie within a deviation of fifty per cent from the reference curve, which, as will be explained later, is the best curve for all data on seven foot packed sections of one-half inch Berl saddles in a four inch column.

The Effect of Packing Technique

The "preferred" orientation of Berl saddles is in a nested position. Naturally, this is just the opposite of completely random orientation of packing pieces. Raschig rings have a number of indistinguishable preferences of orientation in a column, i.e. end to end, side to side, end to side, end to wall, side to wall, etc. Test sections containing isolated locations of groups of pieces arranged preferentially were shown to require lower velocities for flooding than properly packed towers, and flooding originated at such locations. Such lack of random orientation resulted from dry dumping, from dumping into liquid unless packing was dropped piece by piece, and from violent disturbance of the bed after packing, as during flows much greater than those of flooding. Particularly easy to rearrange to the preferred positions are those pieces in the top stratum. Sarchet admitted that at flooding some packing at the top of his column "rattled" around. Flooding at the top of the packing observed by him could have been predicted. He presents photographs which, when compared with those of White, bear out this analysis.

The Selection of a Reference Condition of Column and Packing

A seven foot height of one-half inch Berl saddles in a four inch diameter column has been shown to be sufficient to assure that the effect of height will be negligible. This packing size for this column follows Baker's recommendation. Therefore, these conditions were selected as generally representative and Figure 5 shows data points for air against water in such a column for three different beds of packing. The good agreement among the points established confidence in the methods used to pack the columns and to determine flooding velocities. The curve representing these points is compared with the recommended curve of Sherwood et al. and also with Lobo's curve, for which he used the same data as Sherwood but used averaged values of S/F^3 as mentioned above. The author's curve is reproduced on the plots for other conditions as reference and is so labeled in each case.

The Effect of Properties of the Liquid and Gas

The surface tension varied more than three fold among the various liquids studied but no noticeable trend on a Sherwood type plot due only to surface tension was discovered. The data for all but the 28 centipoise oil correlated well by the method as shown by Figure 6. Considerably better fit for all original data presented here is obtained by plotting as the abcissa $\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)^{\frac{1}{2}}\mu^{0.46}$ rather than the usual abscissa values recommended by Sherwood (see Figure 7). Included in this data is that for carbon dioxide giving a fifty per cent variation of gas density. Extrapolation of any empirical correlation beyond the range of experimental measurements cannot necessarily be expected to yield accurate results. Therefore the materials were so selected to include the ranges to be expected in practice.

Table 3 shows a comparison of the ranges of physical properties covered with those covered by other investigators.

The Effect of Adjusted Surface Tension

The surface tension of water was varied from 72 down to 32 dynes $cm.^{-1}$ by addition of such minute amounts of Sterox that other properties were shown to be unaffected. Figure 8 shows the flooding velocities for air against the solutions are markedly less than those for water and that the lowering is greater with greater surface tension lowering.

Data for the systems of air and aqueous solutions of other surface active agents, namely Aerosol OT and sodium oleate, are presented in Table 4 (in the appendix). The flooding velocities at a given value of adjusted surface tension for all of the additives are in good agreement.

The solutions having adjusted surface tensions foam to a great degree and their tendency to foam is a function of their adjusted surface tension. The surface tension of the pure liquids discussed in the section on the effect of the properties of the liquid varied from 22 to 72 dynes $cm.^{-1}$ but the tendency to foam of any one of them is so small that all of them can be considered non-foaming. The formation of foam is the basis of the explanation given by Newton, Mason, Metcalfe and Summers (20) for the great effect on flooding of adjusted surface tension. All data for the adjusted surface tensions can be correlated as shown in Figure 9 by adding to the abscissa of the Sherwood type co-ordinates a factor of the cube of the ratio of the surface tension

Table 3. Ranges of Variation of Properties of Liquids and Gases

Property	High Value	Low Value	Range	Method
Liquid Viscosity, (Centipoise)				
Author's	28	0.42	65 fold	pure liquids
Sherwood	25	0.91	28	solutions
Bain & Hougen	12	2	6	pure liquids
Schoenborn & Dougherty	35	1	35	pure liquids
Liquid Density, (Lb./Ft.^{3})				
Author's	99	49	2 fold	pure liquids
Sherwood	74	50	1/2	solutions
Bain & Hougen	54	50	1/12	pure liquids
Schoenborn & Dougherty	62	55	1/6	pure liquids
Gas Density, (Lb./Ft.^{3})				
Author's	0.112	0.071	1/2	pure gas
Sherwood	0.113	0.0051	22	pure gas
Bain & Hougen	0.117	0.0054	22	gas mixtures
Liquid Surface Tension, (Dynes/Cm.)				
Author's	73	22	3	pure liquids
Author's	73	32	2	detergent sol'n.
Sherwood	73	26	3	solutions
Schoenborn & Dougherty	73	35	2	pure liquids

of water to that of the solution.

The Effect of the Type of Packing

The curves of Figure 10 show that in case sufficient height is packed, as for example, the seven foot section in the four inch diameter column represented there, the data for flooding a column packed with spheres is satisfactorily correlated by the Sherwood type plot. Values of $\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$ for the one-half inch Intalox saddles are as much as two hundred per cent greater than those for the reference line (one-half inch Berl saddles). Contributing to these high values is the correspondingly high value of surface per unit volume, S, of packing as packed, for the Intalox saddles. This value of 232 $Ft.^2/Ft.^3$ is to be compared with an S value of 128 $Ft.^2/Ft.^3$ for Berl saddles. This curve is for a packed height less than the minimum for making the effect of height negligible. That for the minimum height and greater would undoubtedly lie below the one shown (for 3.5 feet of packing in a four inch column) but in no case has the effect of height been more than about fifty per cent so that this curve could be expected to be considerably too high to be considered well correlated by the Sherwood type plot. Unfortunately an insufficient amount of this new type of packing was available to allow an evaluation of the minimum height for this packing.

The Effect of Hydrophobic Packing and Column Walls

Figure 11 shows that lack of wetting of column walls is an important variable in flooding. Flooding occurred in the column with treated walls consistently at higher velocities than for an ordinary column. On the same plot is a curve for the condition of treated packing and ordinary glass column walls. This should maximize "wall effect" or channeling at the wall, and the column is shown to be more difficult to flood, since ordinates on the plot are as much as fifty per cent greater. The effect of both packing and column walls being hydrophobic is shown by the third curve to be toward greater difficulty of flooding and of the order of magnitude of eighty per cent greater values of the ordinate than for the untreated column and packing. The half inch saddles in a four inch column used in this case conforms to the eight to one ratio of packing size to column diameter recommended as satisfactory by Baker.

SUMMARY AND CONCLUSIONS

Data were collected for flooding of packed towers in which the tower diameter varied from two to eight inches, the packed height from one to sixteen feet and the nominal packing size from one-fourth to one inch. Porcelain Berl saddles, glass spheres and porcelain Intalox saddles were used. Flooding of the towers was studied using the systems of water, ethanol, toluene, methyl ethyl ketone, carbon tetrachloride, kerosene, and Capella Oil with air, and also of Capella Oil with carbon dioxide. In addition, data were obtained for the flooding velocities with water and air of a column containing packing which had been treated so as to be hydrophobic, of a column whose walls had been so treated and containing ordinary packing, and of a treated column containing treated packing. Data were also taken on a column being flooded with air and aqueous solutions of such surface active agents as Sterox SK, Aerosol OT and sodium oleate.

Based on consideration of these original data the following unique conclusions have been drawn:

(1) A change in the packed height may alter the flooding velocity in a packed column by as much as seventy per cent but for any column there is a minimum height above which no further effect of height is noticeable. This variation in flooding velocities is due to the distribution of liquid in the column and to wall effects and becomes negligible at high liquid rates (above two and one-half Lb./Sec.Ft.^{2})

(2) Column diameter has negligible effect on flooding if the

ratio of column diameter to nominal packing diameter is constant at eight to one or greater. For the same size of packing in each of the columns, the flooding velocities are a function of tower diameter.

(3) Lack of any noticeable trend in the data for the flooding of a column of given diameter with variation of the size of the Berl saddles has led to the conclusion that the Sherwood correlation in general fits data for all sizes of this packing. For any data obtained here the maximum deviation from Sherwood's recommended curve is about fifty per cent.

(4) Flooding characteristics of solid spheres are not sensitive to the method used for packing. There is no noticeable settling after packing; damage to the packing itself or to the column (packing support, etc.) are the primary factors in choosing the packing method. For hollow type packings, noticeably the saddle types, flooding is affected greatly by the method of packing and by subsequent treatment.

(5) Data for flooding of a packed column with various liquids having ranges of density from 49 to 99 Lb./Ft.^{3}, of viscosity from 0.4 to 28 centipoise and of surface tension from 22 to 72 dynes/cm. using air and carbon dioxide are well correlated by the method of Sherwood, except for the high viscosity liquids. Variation on the plot of data for the 28 centipoise oil is as much as ninety per cent (of the higher values). This variation is less when the data was plotted as $\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$ versus $\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}\mu^{0.16}$.

(6) Lowering the surface tension by addition of some surface active materials greatly reduces the velocities and resulting data

are not correlated by the Sherwood type plot. However, these data can be well correlated by including in the abscissa, as a factor, the cube of the ratio of the surface tension of water to that of the solution.

(7) The Sherwood correlation is satisfactory for Berl saddles and for solid spheres, within the limits of good practice as to packed height and the ratio of column diameter to packing size. Deviation of data for Intalox saddles from the Sherwood curve is too great for accurate representation on the same curve as for other types of packing.

(8) Reducing the "wetability" of the column wall, the packing, or both, increases the velocities required for flooding, each to a greater extent in that order. The effect for treated walls or for treated walls and packing is a constant over the whole range of liquid rates studied. The case in which only the packing was treated represents "maximum wall effect" and hence the effect becomes negligible at high liquid rates.

(9) There is insufficient difference between the graphical pressure drop — gas rate flood point and the visual point, based on observation of the flooding of the packed section, to justify explanation of any discrepancies between sets of data, as has been attempted in the literature. The graphical method is most precisely reproducible and is independent of human error in observation and judgement. The condition at which liquid stands any measured height above the packing is beyond the flooding point.

(10) When determined by displacement of water, the difference between dry voids and drained wet voids is negligible and any effect

due to ohe choice between them has been overshadowed in the cases of most investigators by insufficient care in selecting the method of determination.

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APPENDIX

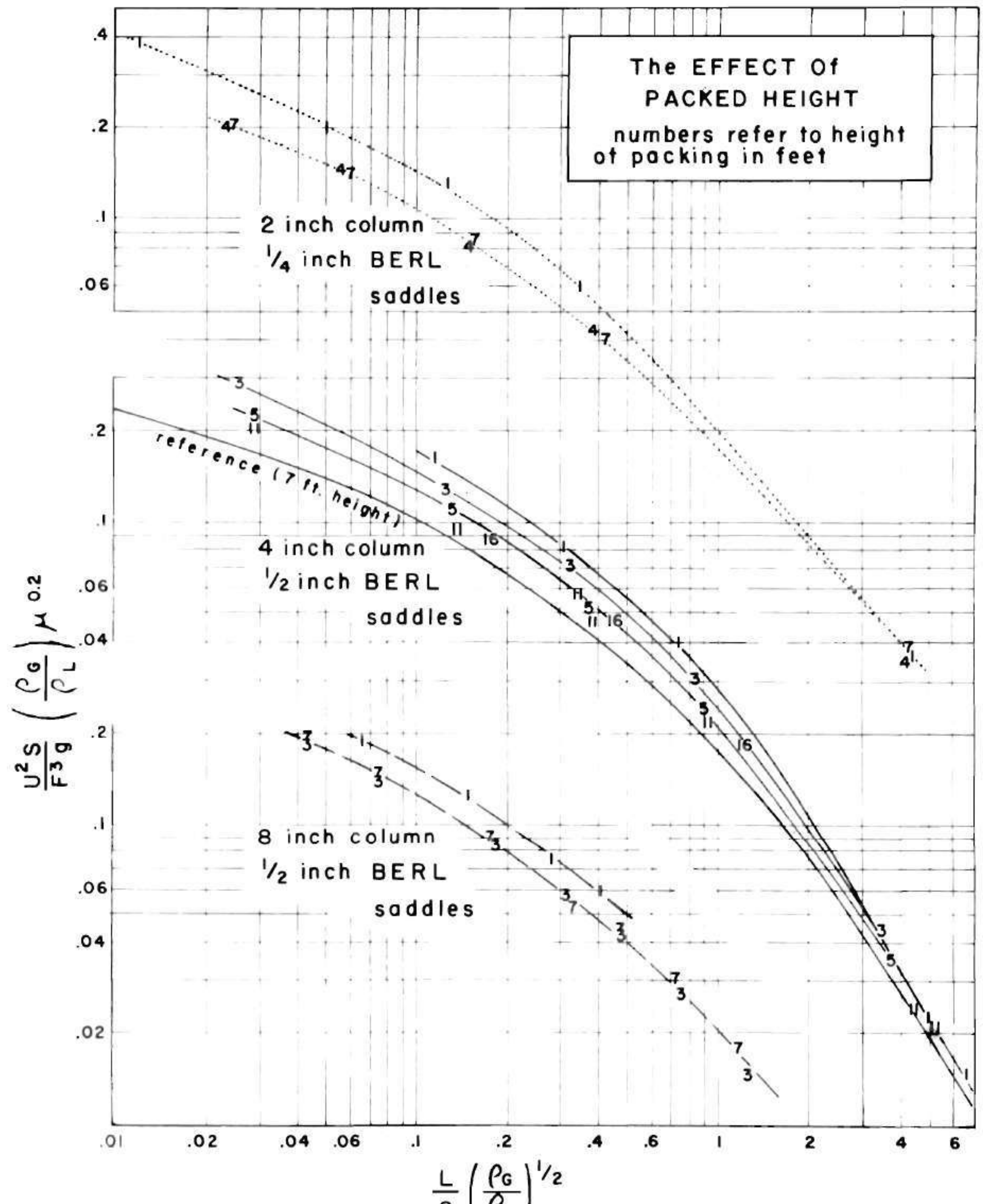
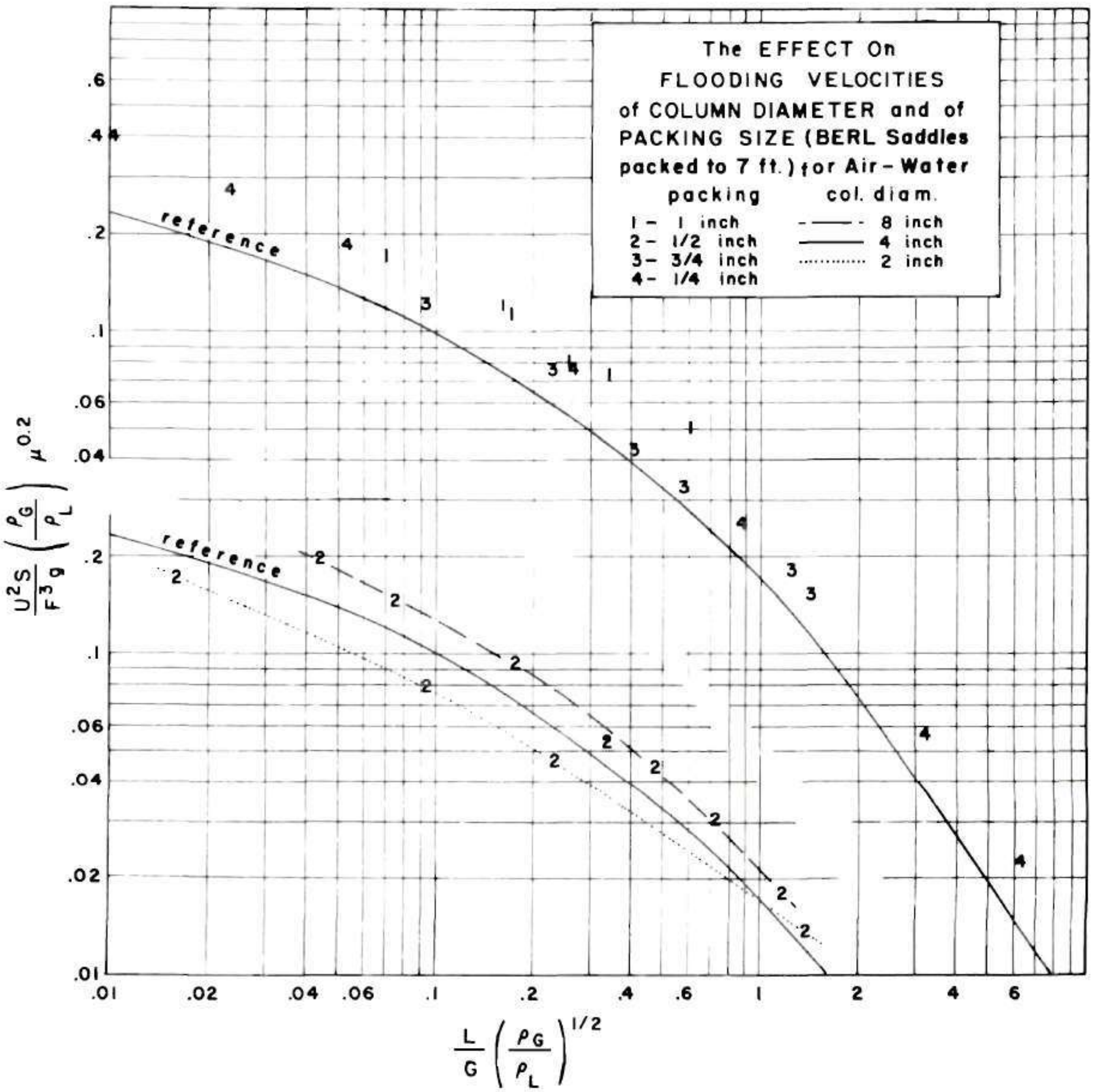

The EFFECT Of PACKED HEIGHT
numbers refer to height of packing in feet
2 inch column
1/4 inch BERL saddles
4 inch column
1/2 inch BERL saddles
reference (7 ft. height)
8 inch column
1/2 inch BERL saddles
$\frac{U^2 S}{F^3 g}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$

Figure 3.



The EFFECT On FLOODING VELOCITIES of COLUMN DIAMETER and of PACKING SIZE (BERL Saddles packed to 7 ft.) for Air-Water
packing
1 - 1 inch
2 - 1/2 inch
3 - 3/4 inch
4 - 1/4 inch
col. diam.
8 inch
4 inch
2 inch
reference
reference
$\frac{U^2S}{F^3g}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$

Figure 4.

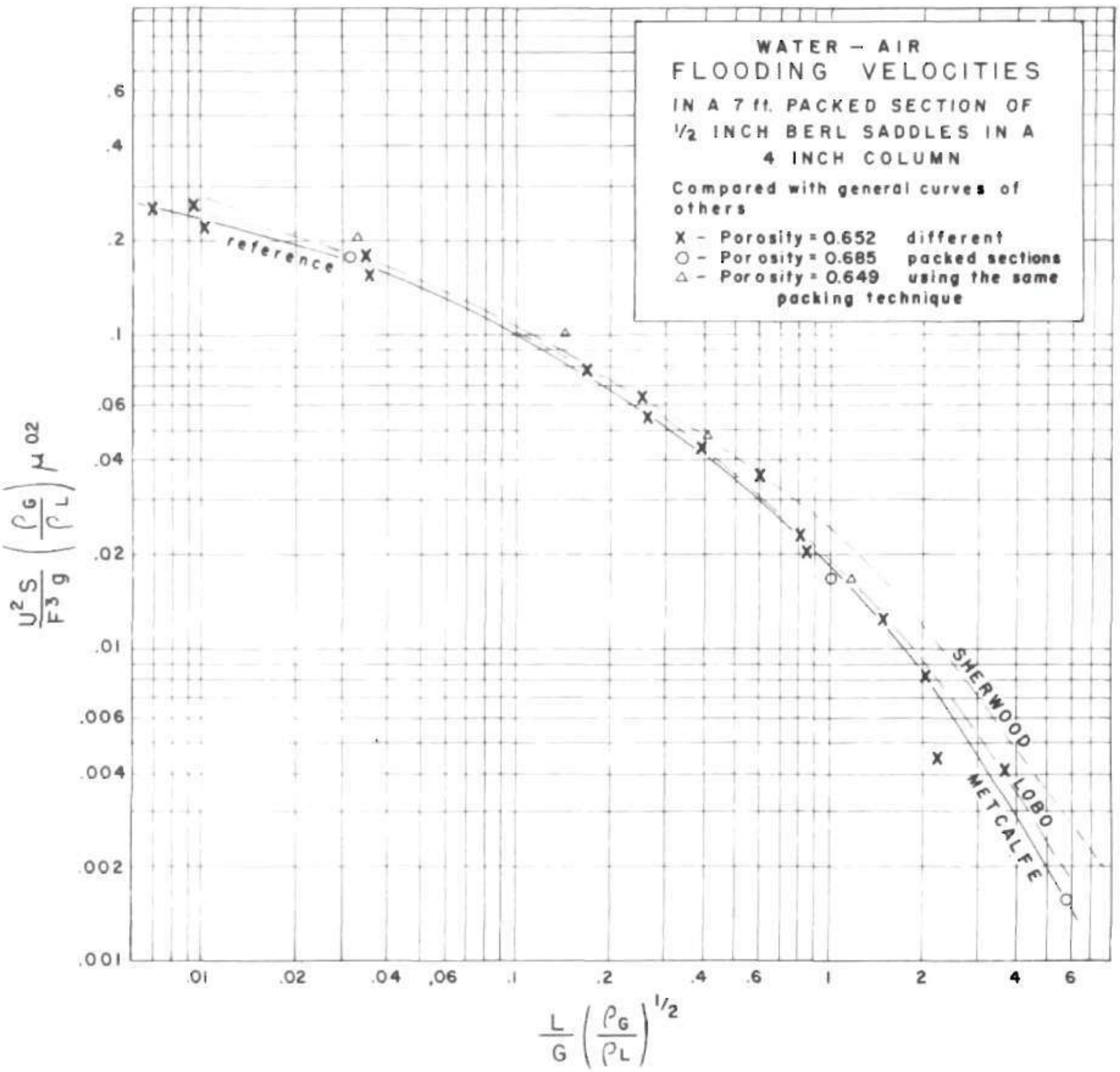

WATER – AIR
FLOODING VELOCITIES
IN A 7 ft. PACKED SECTION OF
1/2 INCH BERL SADDLES IN A
4 INCH COLUMN
Compared with general curves of others
X – Porosity = 0.652
O – Porosity = 0.685
△ – Porosity = 0.649
different packed sections using the same packing technique
reference
SHERWOOD
LOBO
METCALFE
.6
.4
.2
.1
.06
.04
.02
.01
.006
.004
.002
.001
.01
.02
.04
.06
.1
.2
.4
.6
1
2
4
6

Figure 5.

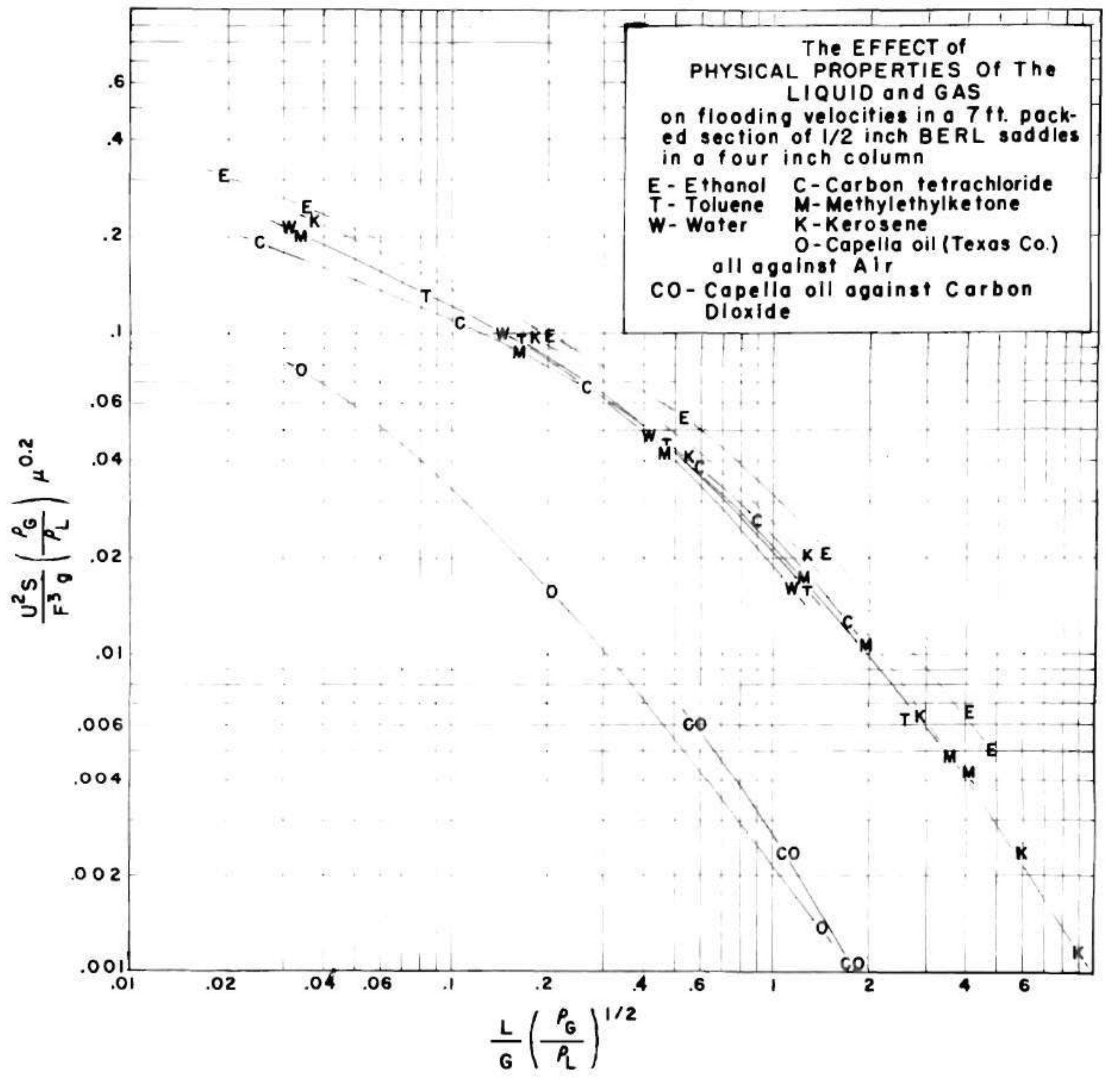

The EFFECT of PHYSICAL PROPERTIES Of The LIQUID and GAS on flooding velocities in a 7 ft. packed section of 1/2 inch BERL saddles in a four inch column
E - Ethanol
T - Toluene
W - Water
C - Carbon tetrachloride
M - Methylethylketone
K - Kerosene
O - Capella oil (Texas Co.)
all against Air
CO - Capella oil against Carbon Dioxide
$\frac{U^2 S}{F^3 g}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$

Figure 6.

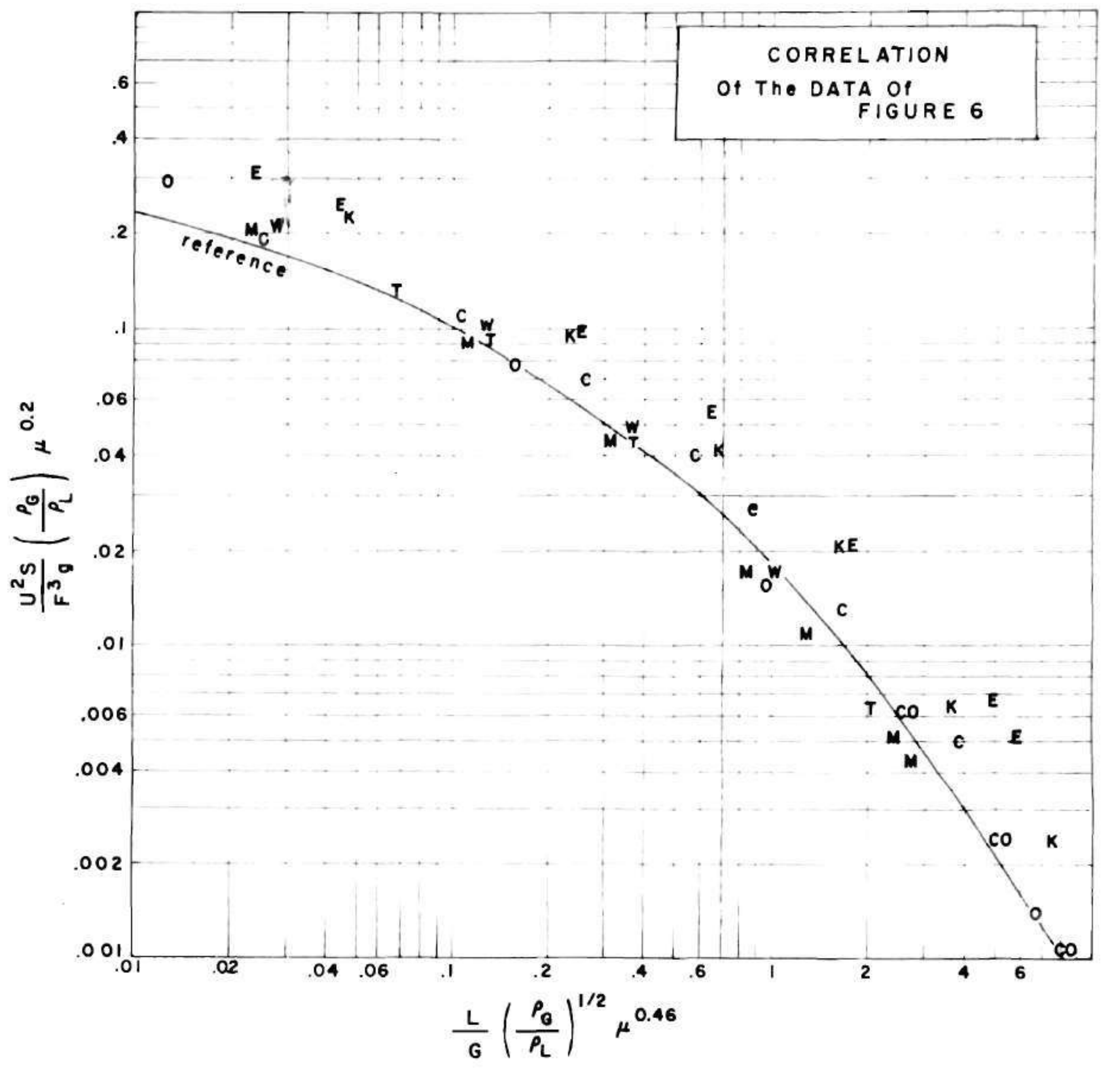

CORRELATION
Of The DATA Of
FIGURE 6
reference
$\frac{U^2 S}{F^3 g} \left(\frac{\rho_G}{\rho_L}\right) \mu^{0.2}$
$\frac{L}{G} \left(\frac{\rho_G}{\rho_L}\right)^{1/2} \mu^{0.46}$
.6
.4
.2
.1
.06
.04
.02
.01
.006
.004
.002
.001
.01
.02
.04
.06
.1
.2
.4
.6
1
2
4
6

Figure 7.

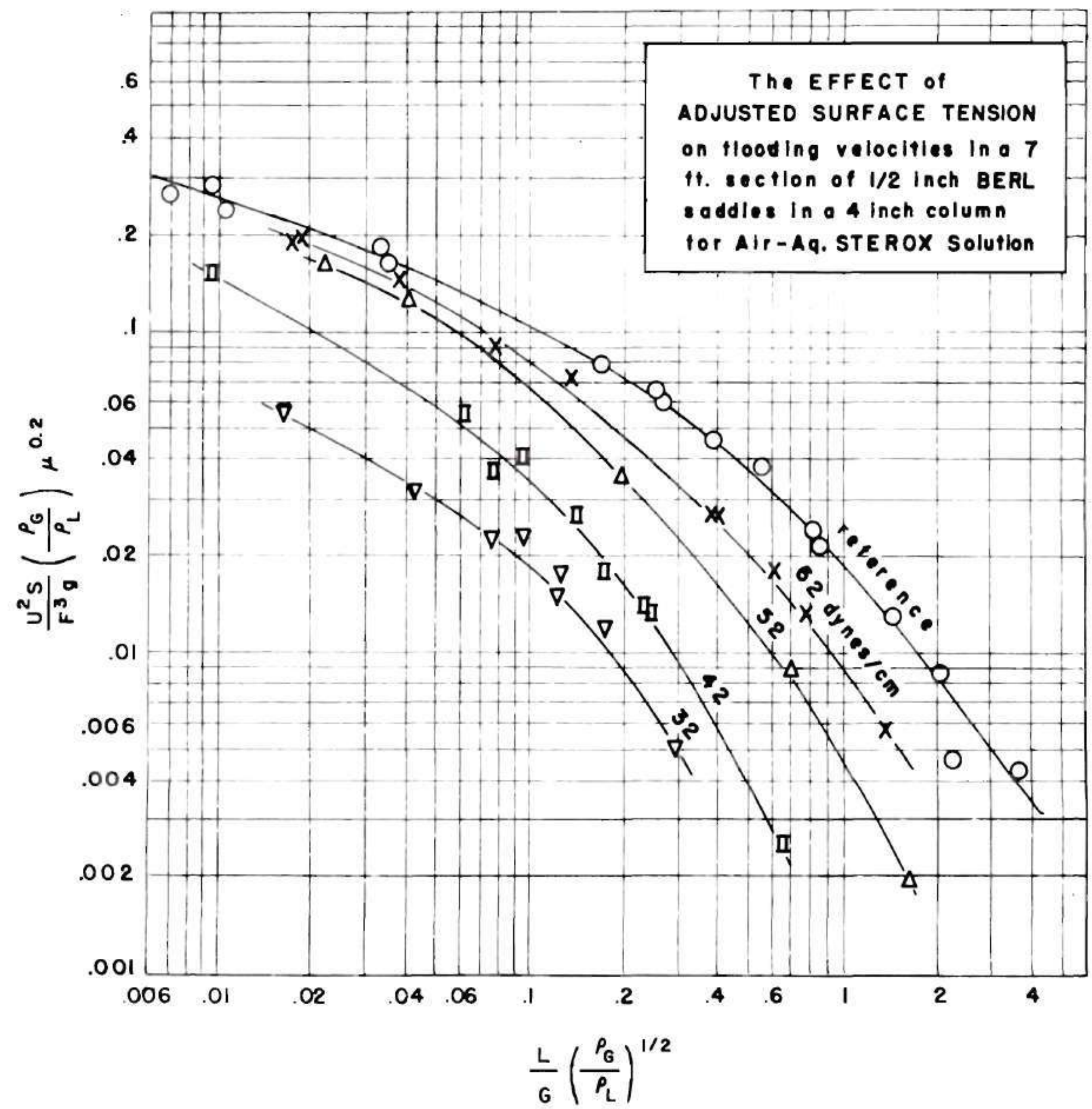
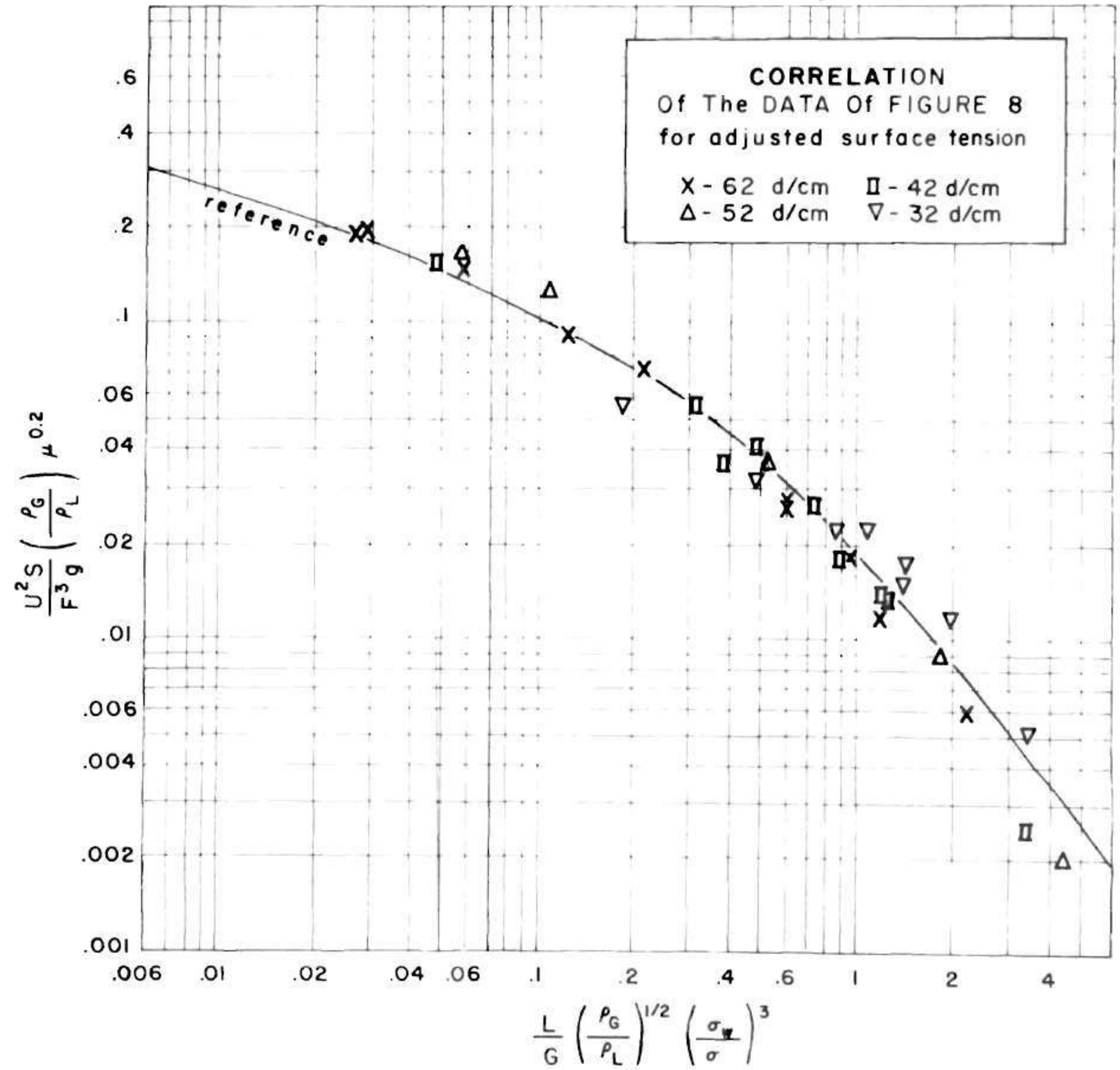

The EFFECT of
ADJUSTED SURFACE TENSION
on flooding velocities in a 7
ft. section of 1/2 inch BERL
saddles in a 4 inch column
for Air-Aq. STEROX Solution
reference
62 dynes/cm
52
42
32
$\frac{U^2 S}{F^3 g}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$
.6
.4
.2
.1
.06
.04
.02
.01
.006
.004
.002
.001
.006
.01
.02
.04
.06
.1
.2
.4
.6
1
2
4

Figure 8.



CORRELATION
Of The DATA Of FIGURE 8
for adjusted surface tension
X - 62 d/cm
Δ - 52 d/cm
Π - 42 d/cm
∇ - 32 d/cm
reference
.6
.4
.2
.1
.06
.04
.02
.01
.006
.004
.002
.001
.006
.01
.02
.04
.06
.1
.2
.4
.6
1
2
4
$\frac{U^2 S}{F^3 g}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}\left(\frac{\sigma_w}{\sigma}\right)^3$

Figure 9.

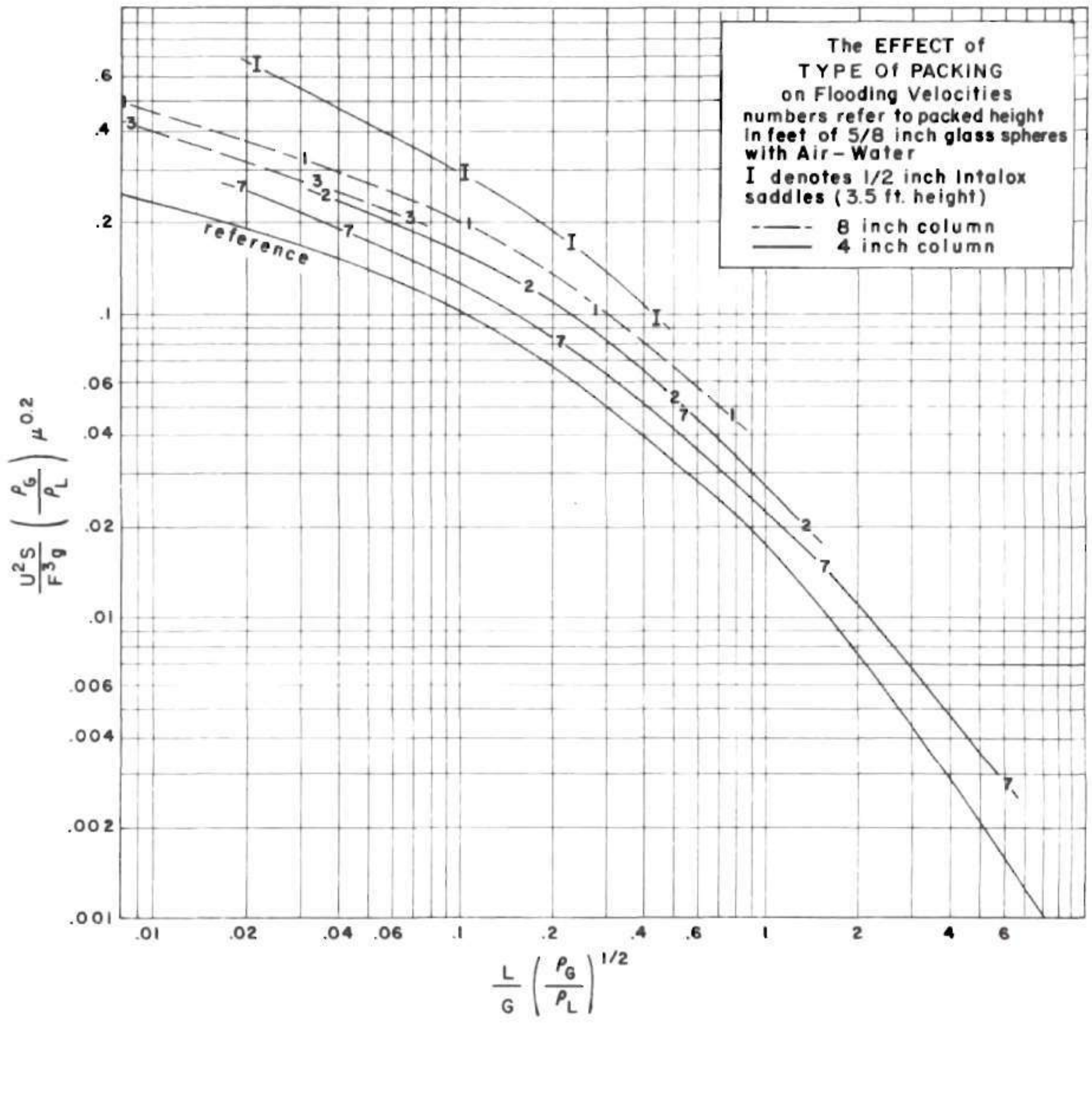

The EFFECT of
TYPE Of PACKING
on Flooding Velocities
numbers refer to packed height in feet of 5/8 inch glass spheres with Air-Water
I denotes 1/2 inch Intalox saddles (3.5 ft. height)
8 inch column
4 inch column
reference
$\frac{U^2S}{F^3g}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$
.6
.4
.2
.1
.06
.04
.02
.01
.006
.004
.002
.001
.01
.02
.04
.06
.1
.2
.4
.6
1
2
4
6

Figure 10.

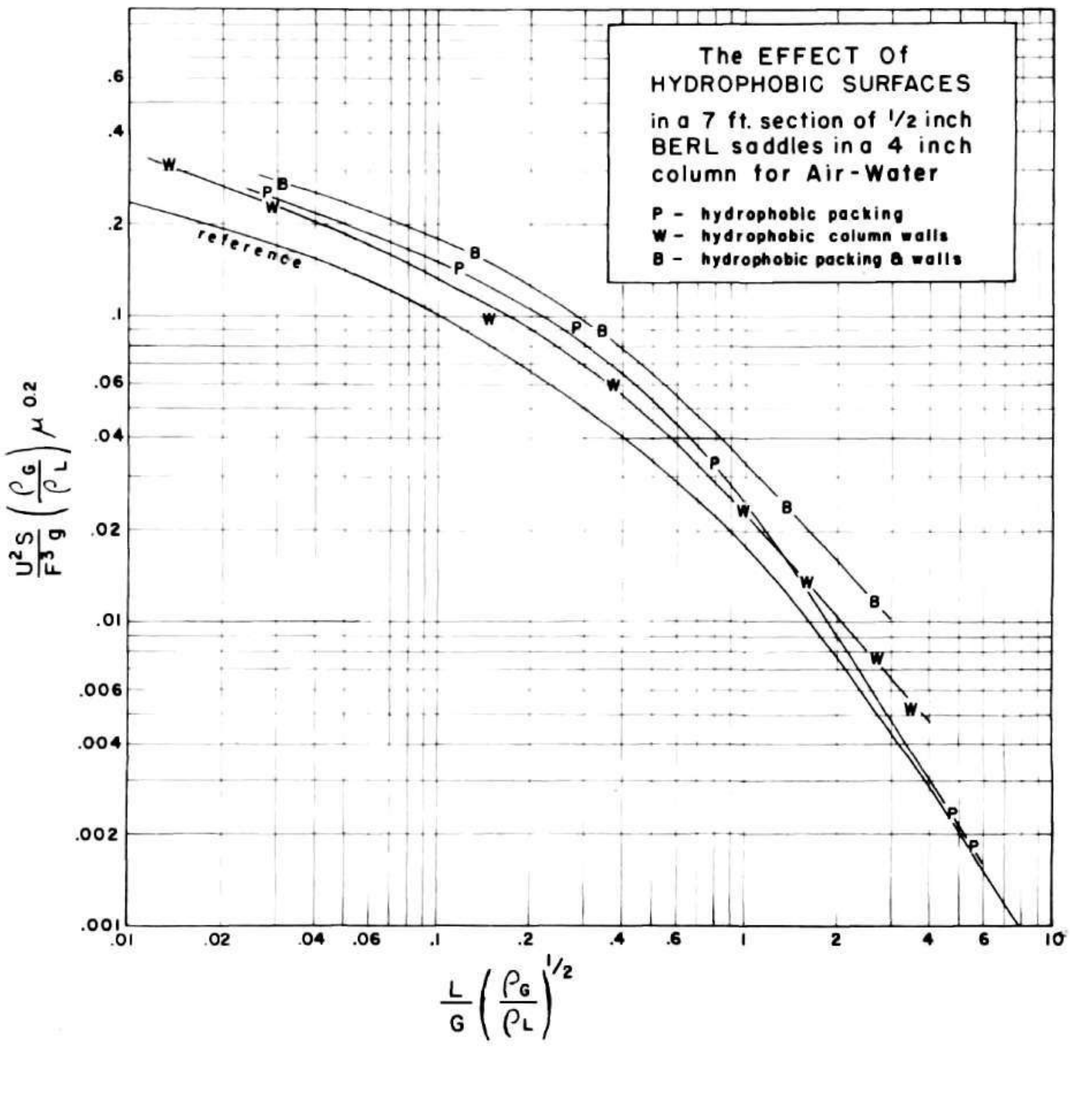

The EFFECT Of
HYDROPHOBIC SURFACES
in a 7 ft. section of 1/2 inch
BERL saddles in a 4 inch
column for Air-Water
P - hydrophobic packing
W - hydrophobic column walls
B - hydrophobic packing & walls
reference
$\frac{U^2 S}{F^3 g}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$
$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$

Figure 11.

Table 4. Flooding Velocities

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$
2 " Column, $\frac{1}{4}$ " Berl saddles, 1 Ft. packed height, porosity 0.630 Water: 62.2 Lb./Ft.^{3}, 0.750 centipoise, 72 dynes/cm. Air: 0.0710 Lb./Ft.^{3}			
0.0900	0.254	0.379	0.0119
0.270	0.185	0.202	0.0492
0.540	0.148	0.129	0.123
1.03	0.101	0.0596	0.344
3.28	0.0254	0.00379	4.37
4 Ft. packed height, porosity 0.642			
0.135	0.192	0.199	0.0237
0.270	0.163	0.142	0.0561
0.540	0.123	0.0815	0.148
1.03	0.0897	0.0432	0.386
3.28	0.0254	0.00347	4.37
7.5 Ft. packed height, porosity 0.631			
0.135	0.184	0.201	0.0248
0.270	0.153	0.141	0.0595
0.540	0.120	0.0867	0.152
1.03	0.0834	0.0417	0.415
3.28	0.0254	0.00386	4.37
$\frac{1}{2}$ " Berl saddles, 4 Ft. packed height, porosity 0.705			
0.135	0.333	0.228	0.0137
0.270	0.286	0.163	0.0319
0.540	0.235	0.114	0.0777
1.03	0.168	0.0575	0.207
3.28	0.0837	0.0144	1.33
6.39	0.0346	0.00246	6.24

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$
7 Ft. packed height, porosity 0.700			
0.135	0.286	0.174	0.0159
0.540	0.193	0.0792	0.0944
1.03	0.149	0.0470	0.233
3.28	0.0798	0.0136	1.39
6.39	0.0342	0.00248	6.32
4 " Column, $\frac{1}{4}$ " Berl saddles, 7 Ft. packed height, porosity 0.582			
0.0631	0.218	0.400	0.00980
0.126	0.181	0.275	0.0236
0.240	0.150	0.189	0.0541
0.770	0.0970	0.0791	0.268
1.50	0.0560	0.0264	0.898
2.51	0.0262	0.00576	3.23
3.13	0.0164	0.00226	6.45
3.96	0.0115	0.00111	11.63
$\frac{1}{2}$ " Berl saddles, 1 Ft. packed height, porosity 0.651			
0.240	0.296	0.270	0.0274
0.770	0.226	0.157	0.115
1.50	0.164	0.0828	0.303
2.51	0.114	0.0400	0.743
3.96	0.0270	0.00225	4.96
4.36	0.0220	0.00149	6.70
3.5 Ft. packed height, porosity 0.655			
0.240	0.311	0.289	0.0261
0.770	0.208	0.129	0.125
1.50	0.156	0.0727	0.324
2.51	0.101	0.0305	0.838
3.96	0.0380	0.00432	3.52

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$	
		7 Ft. packed height, porosity		0.652
0.0845	0.300	0.271	0.00950	
0.230	0.240	0.173	0.0326	
1.07	0.144	0.0622	0.247	
1.78	0.107	0.0352	0.599	
2.51	0.0380	0.00444	2.25	
0.0845	0.276	0.228	0.0103	
0.230	0.226	0.153	0.0344	
0.780	0.158	0.0748	0.167	
1.36	0.120	0.0432	0.385	
2.08	0.0820	0.0202	0.852	
2.83	0.0640	0.0123	1.49	
3.14	0.0520	0.00811	2.04	
3.96	0.0368	0.00406	3.64	
0.0633	0.292	0.255	0.00717	
1.07	0.137	0.0562	0.262	
2.07	0.0870	0.0228	0.802	
			porosity	0.649
0.241	0.259	0.208	0.0313	
0.770	0.179	0.0997	0.143	
1.50	0.124	0.0479	0.408	
2.51	0.0730	0.0166	1.16	
			porosity	0.685
0.241	0.274	0.179	0.0296	
2.51	0.0840	0.0169	1.01	
4.37	0.0256	0.00157	5.76	

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$
11 Ft. packed height, porosity 0.669			
0.241	0.281	0.213	0.0289
0.770	0.188	0.0953	0.138
1.50	0.147	0.0583	0.344
1.50	0.132	0.0470	0.383
2.51	0.0920	0.0228	0.921
3.96	0.0300	0.0243	4.46
4.37	0.0284	0.00218	5.19
16 Ft. packed height, porosity 0.623			
0.770	0.152	0.0878	0.171
1.50	0.112	0.0476	0.451
2.51	0.0690	0.0181	1.23
3/4 " Berl saddles, 7 Ft. packed height, porosity 0.701			
0.770	0.281	0.125	0.0925
1.50	0.221	0.0774	0.229
2.00	0.165	0.0431	0.410
2.51	0.145	0.0333	0.584
3.13	0.121	0.0232	0.873
3.96	0.108	0.0185	1.24
4.18	0.100	0.0159	1.41
1 " Berl saddles, 7 Ft. packed height, porosity 0.700			
0.770	0.368	0.171	0.0706
1.50	0.298	0.112	0.170
2.00	0.262	0.0867	0.258

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$
			porosity 0.700
1.50	0.311	0.122	0.162
2.51	0.246	0.0764	0.344
3.75	0.205	0.0531	0.618
5/8 " glass spheres, 2 Ft. packed height, porosity 0.434			
0.241	0.218	0.244	0.0372
0.770	0.154	0.122	0.169
1.50	0.101	0.0518	0.503
2.51	0.0620	0.0197	1.37
7 Ft. packed height, porosity 0.417			
0.127	0.221	0.263	0.0193
0.241	0.187	0.188	0.0434
0.770	0.122	0.0800	0.213
1.50	0.0930	0.0465	0.543
2.51	0.0540	0.0157	1.57
4.18	0.0227	0.00277	6.21
½ " Intalox saddles, 3.5 Ft. packed height, porosity 0.695			
0.241	0.380	0.661	0.0214
0.770	0.251	0.288	0.104
1.36	0.195	0.174	0.236
1.93	0.145	0.0962	0.449

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$
Hydrophobic $\frac{1}{2}$" Berl saddles, 7 Ft. packed height, porosity 0.661			
0.241	0.294	0.247	0.0276
0.770	0.224	0.144	0.116
1.50	0.134	0.0513	0.378
2.51	0.108	0.0333	0.784
3.96	0.0286	0.00234	4.68
4.18	0.0254	0.00184	5.55
4" diameter column with walls treated to be hydrophobic, Hydrophobic $\frac{1}{2}$" Berl saddles, 7 Ft. packed height, porosity 0.614			
0.241	0.262	0.279	0.0310
0.770	0.199	0.161	0.131
1.50	0.149	0.0900	0.339
3.13	0.0770	0.0240	1.37
4.18	0.0540	0.0118	2.61
Ordinary $\frac{1}{2}$" Berl saddles, 7 Ft. packed height, porosity 0.650			
0.0633	0.360	0.403	0.00594
0.127	0.316	0.310	0.0135
0.241	0.276	0.236	0.0294
0.770	0.177	0.0972	0.147
1.50	0.136	0.0573	0.372
2.51	0.0860	0.0230	0.985
3.13	0.0660	0.0135	1.59
3.96	0.0492	0.00751	2.72
4.18	0.0407	0.00513	3.46

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}\mu^{0.46}$

4 " Column, $\frac{1}{2}$ " Berl saddles, 7 Ft. packed height, porosity 0.649
Ethanol: Density 49.2 Lb./Ft.^{3}, viscosity 1.5 centipoise, surface tension 22.3 dynes/cm.
Air: Density 0.0710 Lb./Ft.^{3}

0.114	0.259	0.305	0.0192	0.0231
0.217	0.232	0.246	0.0360	0.0434
0.693	0.146	0.0968	0.204	0.246
1.35	0.109	0.0540	0.537	0.647
2.26	0.0670	0.0204	1.47	1.77
3.57	0.0381	0.00660	4.07	4.90
3.76	0.0332	0.00502	4.92	5.93

Toluene: Density 55.1 Lb./Ft.^{3}, viscosity 0.59 centipoise, surface tension 28.4 dynes/cm.

0.436	0.187	0.138	0.0843	0.0659
0.722	0.158	0.0940	0.165	0.129
1.41	0.109	0.0448	0.467	0.365
2.36	0.0660	0.0164	1.29	1.01
2.94	0.0410	0.00634	2.60	2.03

Carbon Tetrachloride: Density 99.5 Lb./Ft.^{3}, viscosity 0.97 centipoise, surface tension 26.7 dynes/cm.

0.290	0.277	0.157	0.0278	0.0274
0.290	0.305	0.191	0.0253	0.0249
0.290	0.305	0.191	0.0253	0.0249
0.927	0.232	0.110	0.107	0.105
1.81	0.183	0.0688	0.262	0.258
3.02	0.139	0.0396	0.580	0.572
3.77	0.113	0.0262	0.889	0.875
5.03	0.0790	0.0128	1.70	1.67
7.05	0.0490	0.00492	3.84	3.80

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2 S}{g F^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}\mu^{.46}$
Methyl Ethyl Ketone: Density 50.1 Lb./Ft.^{3}, viscosity 0.42 centipoise, surface tension 24.6 dynes/cm.				
0.219	0.241	0.201	0.0340	0.0229
0.700	0.162	0.0904	0.162	0.109
1.36	0.113	0.0440	0.453	0.304
2.28	0.0700	0.0169	1.22	0.820
2.84	0.0560	0.0108	1.91	1.28
3.60	0.0380	0.00498	3.56	2.40
3.80	0.0352	0.00428	4.05	2.72
Kerosene: Density 50.2 Lb./Ft.^{3}, viscosity 1.61 centipoise, surface tension 27.8 dynes/cm.				
0.219	0.222	0.222	0.0370	0.0460
0.700	0.144	0.0933	0.182	0.227
1.36	0.0950	0.0406	0.583	0.670
2.28	0.0670	0.0202	1.28	1.60
2.84	0.0376	0.00636	2.85	3.54
3.60	0.0228	0.00234	5.94	7.39
3.80	0.0161	0.00117	8.84	11.0
Capella Oil: Density 55.0 Lb./Ft.^{3}, viscosity 28 centipoise, surface tension 31.7 dynes/cm.				
0.0148	0.199	0.288	0.00267	0.0123
0.0970	0.103	0.0771	0.0338	0.156
0.270	0.0466	0.0158	0.208	0.963
0.555	0.0138	0.00138	1.44	6.68
0.590	0.0114	0.000944	1.86	8.61

Table 4. Flooding Velocities (Continued)

Capella Oil: Density 55.0 Lb./Ft.^{3}, viscosity 28 centipoise, surface tension 31.7 dynes/cm.
Carbon Dioxide: Density 0.113 Lb./Ft.^{3}

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}\mu^{0.44}$
0.461	0.0364	0.00601	0.574	2.66
0.555	0.0228	0.00235	1.11	5.11
0.590	0.0152	0.00104	1.76	8.17

4 " Diameter Column, ½ " Berl saddles, 7 Ft. packed height, porosity 0.660
Aqueous Sterox Solution: Density 62.2 Lb./Ft.^{3}, viscosity 0.75 centipoise, surface tension 62 dynes/cm.
Air: Density 0.0710 Lb./Ft.^{3}

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}\left(\frac{\sigma_w}{\sigma}\right)^3$
0.127	0.247	0.179	0.0173	0.0270
0.137	0.252	0.186	0.0184	0.0286
0.241	0.218	0.139	0.0372	0.0580
0.622	0.153	0.0687	0.137	0.214
1.06	0.0920	0.0249	0.392	0.610
1.37	0.0760	0.0105	0.609	0.950
1.79	0.0434	0.00552	1.39	2.17
2.51	0.0125	0.000458	6.78	10.6

Surface tension 52 dynes/cm.

0.148	0.229	0.154	0.0218	0.0578
0.241	0.201	0.119	0.0404	0.108
0.612	0.106	0.0330	0.195	0.518
1.06	0.0530	0.00824	0.679	1.81
1.21	0.0249	0.00182	1.64	4.36

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}\left(\frac{\sigma_w}{\sigma}\right)^3$
		Surface tension 42 dynes/cm.		
0.0633	0.222	0.145	0.00962	0.0485
0.241	0.132	0.0512	0.0615	0.310
0.316	0.113	0.0376	0.0945	0.477
0.390	0.0920	0.0249	0.143	0.723
0.464	0.0650	0.0124	0.241	1.22
0.548	0.0280	0.00231	0.661	3.34
		Surface tension 32 dynes/cm.		
0.0633	0.132	0.0511	0.0162	0.184
0.126	0.100	0.0294	0.0427	0.486
0.188	0.0840	0.0207	0.0754	
0.251	0.0690	0.0140	0.123	1.40
0.274	0.0740	0.0161	0.125	1.42
0.316	0.0610	0.0109	0.175	1.99
0.359	0.0404	0.00479	0.299	3.40
0.390	0.0173	0.000879	0.761	8.65
0.390	0.0122	0.000437	1.08	12.3

Aqueous Aerosol: Density 62.2 Lb./Ft.^{3}, viscosity 0.75 centipoise, surface tension 44 dynes/cm.
Air: Density 0.0710 Lb./Ft.^{3}

0.0633	0.248	0.181	0.00861
0.127	0.200	0.118	0.0214
0.127	0.202	0.120	0.0212
0.241	0.161	0.0762	0.0504
0.464	0.0690	0.0140	0.227
0.548	0.0300	0.00265	0.617
0.770	0.0153	0.000688	1.70

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$

Aqueous Sodium Oleate: Density 62.2 Lb./Ft.^{3}, viscosity 0.75 centipoise, surface tension 62 dynes/cm.
Air: Density 0.071 Lb./Ft.^{3}.

0.0633	0.281	0.232	0.00760
0.127	0.249	0.182	0.0172
0.241	0.222	0.144	0.0366
0.464	0.179	0.0939	0.0875
1.36	0.108	0.0342	0.425
2.36	0.0640	0.0120	1.25

8 " Column, ½ " Berl saddles, 1 Ft. packed height, porosity 0.681
Water: Density 62.2 Lb./Ft.^{3}, viscosity 0.74 centipoise, surface tension 72 dynes/cm.
Air: Density 0.071 Lb./Ft.^{3}

0.541	0.275	0.186	0.0664
1.00	0.226	0.125	0.150
1.45	0.173	0.0741	0.283
1.91	0.150	0.0591	0.417

3.5 Ft. packed height, porosity 0.686

0.363	0.280	0.186	0.0438
0.540	0.244	0.141	0.0748
1.01	0.190	0.0850	0.181
1.46	0.156	0.0576	0.317
1.91	0.135	0.0432	0.479
2.39	0.107	0.0271	0.755
2.96	0.078	0.0144	1.28

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2 S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$
7 Ft. packed height, porosity 0.681			
0.363	0.283	0.198	0.0433
0.540	0.245	0.148	0.0745
1.01	0.195	0.0938	0.176
1.46	0.147	0.0533	0.336
1.91	0.136	0.0450	0.475
2.39	0.111	0.0304	0.728
2.96	0.0853	0.180	1.17
3/4 " Berl saddles, 3.5 Ft. packed height, porosity 0.653			
1.46	0.259	0.152	0.191
1.92	0.240	0.131	0.269
2.40	0.205	0.0953	0.394
2.68	0.192	0.0836	0.470
1 " Berl saddles, 1 Ft. packed height, porosity 0.690			
2.96	0.275	0.103	0.363
3.5 Ft. packed height, porosity 0.746			
2.39	0.302	0.0807	0.268
2.67	0.283	0.0709	0.319
2.96	0.241	0.0514	0.414
5/8 " Glass Spheres, 1 Ft. packed height, porosity 0.406			
0.0642	0.270	0.491	0.00803
0.206	0.220	0.327	0.0315
0.363	0.189	0.243	0.0647
0.540	0.123	0.102	0.276
1.00	0.171	0.197	0.107
1.91	0.0824	0.0458	0.784

Table 4. Flooding Velocities (Continued)

L, Lb./Sec.Ft.^{2}	G, Lb./Sec.Ft.^{2}	$\frac{U^2S}{gF^3}\left(\frac{\rho_G}{\rho_L}\right)\mu^{0.2}$	$\frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{1/2}$
		3.5 Ft. packed height, porosity	0.420
0.0642	0.259	0.419	0.00835
0.206	0.206	0.264	0.0337
0.363	0.180	0.203	0.0680

VITA

Tom Brooks Metcalfe was born 26 February 1920 on a farm near Smithville, Texas, to Joseph and Louise Taylor Metcalfe. He attended the schools of McDade, Texas for nine years and was graduated from Elgin High School, Elgin, Texas in 1937.

The B. S. degree in Chemical Engineering was conferred on him in 1941 by the University of Texas, after which he was employed for two and one-half years at Freeport, Texas, by the Dow Chemical Company. His next two years were spent on active duty with the Naval Reserve in the Pacific Theater as an engineering officer, afloat.

On 3 July 1944 Brooks was married to Jean Soward of Robstown, Texas. They have two daughters, Gwen, aged five years, and Linda Gail, two years.

Brooks received the M. S. degree in Chemical Engineering from the University of Texas in 1947 and was employed by the Bureau of Industrial Chemistry there for two years. In the fall of 1950 he entered the Georgia Institute of Technology. He was employed by the State Engineering Experiment Station during 1951 and has held a fellowship from the Research Committee of the Institute during 1952.